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A PLAN FOR THE RESEARCH AND DEVELOPMENT OF A SYNTHETIC APERTURE RADARGRAPHIC TOPOGRAPHY SYSTEM

(Phase I Study Final Report - JPL Contract No. 956404)

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1. OBJECTIVES AND SCOPE OF WORK

THE FUNDAMENTAL TASK OF THE RADARGRAPHIC SYSTEM

The fundamental task of the "Radargraphics System" is to extract the elevation topography that is inherent in sets of SAR data of areas viewed from different angles. For earth applications, this could entail combining data from different missions to construct the required 2 or more overlapping views. The VRM(Venus Radar Mapper) mission should provide data from opposite side views of the same area and some same side views at different angles.

The purpose of this proposed work would be to perform research, development, and to fabricate a synthetic aperture radar(SAR) "Radargraphics System". This system will be used for extraction of topographic information obtained by the SIR-B, SIR-C ,SIR-D ,the SAMEX free flyer, and VRM (Venus Radar Mapper). In addition we will study the selected USGS aircraft mission data to determine the feasibility of using this data for topography generation. Section 2 gives a brief descriptive summary of these missions and their mission data characteristics.

The research and development for a "Radargraphics System" using SAR imagery not only involves the development of special computer hardware and software, but also involves various aspects of the total radar system. The orientation of the radar platform and its orbital position referenced to the radar data will be needed. The return signal will contain information on (1) the small scattering parameters of the surface as well as (2) the gross parameters of the average slope, range and elevation. The radar system processing functions will need to be included in the eventual analysis. All these system parameters will be necessary in evaluating and choosing the optimum scheme for extracting the desired elevation information from the "multiple look" SAR data.

DIFFERENCES BETWEEN RADAR AND PHOTO IMAGES REQUIRE NEW METHODS

The SAR(Synthetic Aperture Radar) image of the ground surface is different than that obtained photographically.The SAR images measures true azimuth (in length) and distance from the radar(range) while the camera provides only angular displacemnet in both planes. Hence the SAR image on one axis shows detail that is displaced in range with relief displacement towards the radar platform. The displacement increases as the incidence angle approaches nadir.This contrasts to a photograph where the topography relief displacement decreases as the view direction approaches nadir. The time honored photogrammetry methods of using the human visual ability to perceive depth recovers three-dimensional information by locating the conjugate image points on a stereo pair of photographs taken from different view positions. This process works well for photographic processes because the single eye and the camera have a similar view perspective. Through optics the two eyes can be artifically separated to view the surface relief in the same sense that two seperate cameras view the ground point at contrasting angles. This method is marginal when radar images are substituted for the photographic images because there is no human visual element equivalent of the radar imaging equipment, therefore there is no satisfactory way to simulate the human perception that makes stereo fusion possible. It is now generally accepted that the classic stereo approach used in photogrammetry cannot be applied to radar images except in very limited conditions.[1]

AN ANALYTIC SOLUTION CAPITALIZING ON UNIQUE SAR RADAR PHENOMENA

In the past, efforts to extract topography from SAR data have employed some variation of photogrammetry methods. We feel that a fresh new approach is required that is not perceptual. Also, the approach must capitalize on the unique characteristics of the radar data rather than to attempt to circumvent them. The eventual solution must be analytical for 3 reasons: (1) there is no human equivalent to the radar view perspective, (2) high speed computer methods will be required to process the massive volume of digital data that form the radar images,(3) researchers [2] are now postulating that more than two overlapping images may be required to resolve ambiguity in the radar data. Thus,the conventional photogrammetry human perception methods cannot be applied unless we create some three or four eyed humans.

WHY PRODUCE TOPOGRAPHY FROM SAR RADAR IMAGES ?

The topography obtained from radar images may not provide any overall improvement in the net accuracy of elevation contour mapping over photogrammetry. However, topography maps produced from radar data will provide a new geological perspective. Certain geological features that are masked by the inherently smoothed photogrammetry process should be apparent in the radar images. Changes in slope of a few degrees can change the SAR return signal by a factor of two or more. We have already witnessed many instances where subtle geological features not visible to the eye or from the photograph stand out vividly in the radar images[3].

Other features not in the optimum radar view are distorted or simply fall into voids. Because of the long wavelength, the radar mapping system is not sensitive to minor vegetation and cloud cover. And since the radar system provides its own selected and controlled source of illumination it is not sensitive to the position of the sun as is the photogrammetry method. The long wavelength radar waves penetrate below the surface of the earth to eliminate surface varnish effects of sand and soil that subdue the reflectivity of the geological features to incident light.

Perhaps the honest answer to the title question is that no one can really estimate the scope of eventual benefits from radar derived earth topography. We are confident of three factors: (1) the strictly analytic radargraphic methods will eliminate the effects of the operator's intuitive instincts that characterize the stereo-plotter operation; (2) the topographic detail obtained radargraphically will be a synergistic complement to topography maps obtained photogrammetrically; (3) because of the dense cloud cover on Venus, there is no means of deriving topographic detail photogrammetrically and the "Radargraphic System" is the best hope for the VRM mission. (4) to utilize the backscatter information, it is necessary to remove the topographic radar effects.

INITIAL PROGRAM RESEARCH EMPHASIS

This research will emphasize selection of appropriate theory and solution algorithm,the development of computer software and special computer components for processing corrections for radar geometric distortions and algorithms for extracting elevation data from the radar image data so that radar imagery can be used for topographic mapping. The system should be designed to minimize ground manpower support requirements. The schedule of work calls for having a software version of the system in place to support the SIR-B mission and an engineering prototype model of the system functioning for the SIR-C mission. An operational version of the system would be in place for SIR-D, the SAMEX free flyer, and VRM. Section 4 of this report shows our suggested program schedule for the development of the "Radargraphics System" in relationship to the NASA advanced SAR missions.

THE PROGRAM PHASING

The program is envisioned to consist of four phases. Phase I is an effort to establish the basic concept for a "Radargraphics System" and to define its mission. Phase II is essentially a feasibility effort, while Phase III, IV, & V address the procurement of the total hardware and software system. The results from the Phase I study provides the basis for scoping the Phase II effort. The Phase II effort is a systems analysis effort supporting the formulation of a hardware design specification for the engineering prototype which would be developed in the Phase III design and fabrication part of the program. The Phase II effort also includes the crucial task of modeling and proof testing the algorithms for extracting the elevation topography from radar data.

Bridging the gap between the Phase I conceptual definition and the Phase II method verification effort is a proposed independently sponsored theoretical effort aimed at ferreting out the most promising algorithms for pixel elevation determination. Appendix A of this report provides a technical status report on the ongoing BASD theoretical effort in support of this facet of the program. This effort was started with funds from this study effort and will be supplemented to a much larger extent with BASD internal funds/ BASD feels that this support was needed to provide a measure of continuity to the program and to lay the foundation for the Phase II effort. Section 4 provides a discussion of the programmatic aspects of this study effort.

2. SAR MISSION DATA FOR USGS AND NASA SAR TOPOGRAPHIC MAPPING

RADAR TOPOGRAPHY GRANULARITY IS CONSTRAINED BY THE RADAR IMAGE RESOLUTION CELL (PIXEL)

The radar images returned from the SAR consist of a set of data pixels called resolution cells. The geometric surface area subtended by the resolution cells vary from mission to mission. There is variation within the mission as the antenna pointing direction changes and as different elements of the SAR system are brought into play. The resolution cell areas also vary in size as the viewing platform varies its altitude with all other factors held constant. The limitation on the elevation granularity is set by the size of the largest resolution cell in the data set. If the resolution cell area is a 40 meter square area ,the elevation solution is limited for approximate elevation for a total 40 meter by 40 meter pixel area. A typical range resolution cell for a SIR mission is 25 meters along the track by 30 to 60 meters cross track.

THE SYSTEM MUST PROCESS A MASSIVE SET OF IMAGE DATA TO PRODUCE TOPOGRAPHY

The amount of data to be handled by the "Radargraphics System" is defined by the amount of data from the same areas viewed from different incident angles. Table 2 provides an estimate of the number of view area pixels for the NASA and USGS SAR missions having the potential for producing radar data that could be used to extract topography. A single 100 by 100 kilometer data set could contain 1 to 3 giga-pixels (one billion) . A single elevation data set could require 2 to 4 overlaying radar image data sets as input. Obviously the amount of digital data to be processed is massive. If we are to assume that the bulk of the data must be subjected to computation, we have a throughput problem that must be addressed early in the program.

SYSTEM REQUIREMENTS FOR DATA THROUGHPUT

The ramifications of the elevation solution to the digital processing task must be understood. It will be of no benefit to devise a solution that requires an unrealistic amount of computer time for a solution. As a baseline requirement, we are assuming that data sets corresponding to 100 x100 kilometers each in area (about 3 giga-pixels) should require no more than 8 hours of computer time to produce the topographic data.

NEED FOR SPECIAL COMPUTER COMPONENTS TO TO ACHIEVE THROUGHPUT

If intensive computer operations are unavoidable , we must look at special hardware approaches that will provide a reasonable throughput. We are convinced that the most promising elevation solutions will require image resampling or rectification in some form. Conventional resampling mathematics when performed to the degree of accuracy required to prepare a data set as input for a second analytic operation can tie up a large main frame computer for days at a time. Our hardware resampling system discussed in Appendix B addresses this problem. The elevation solution algorithms themselves will probably dictate the use of some special hardware device for processing arrays or sets of data. Attached array processors can speed up this kind of computational task. We also see the utility of function to function multiple processors. This methodology is very appropriate for the "Radargraphic System " since the nature of the problem is processing multiple data sets in parallel. In addition there are a number of serial operations that can be performed on large data sets. We also anticipate a system requirment for an interactive visual display device for registering overlaping images. Section 3 provides a functional definition of conceptual "Radargraphics System".

FACTORS AFFECTING THE ACCURACY OF THE ELEVATION SOLUTION

The accuracy for determining the elevation is a function of the range cell resolution , the uncertainity in the viewing incidence angle of each data set, the uncertainty interjected by surface roughness, the angular seperation, and the uncertainity in the geographic position of the radar platform. The current mission parameter specifications for the SIR-B orbiter required the orbiter position be known only to about 1 kilometers at any given time. This should be refined by 2 orders of magnitude to obtain the precision required to obtain the elevation accuracy desired (approximatly 50 meters).

The elevation solution will be relative. The data implys only elevation variation from an assumed plane. Thus there has to be some means of defining the mean elevation of this assumed plane. At this point, it is extremely difficult to attach any quantative value on the accuracy for determining terrain elevation. This information can probably only be determined empirically using suitable SAR data.

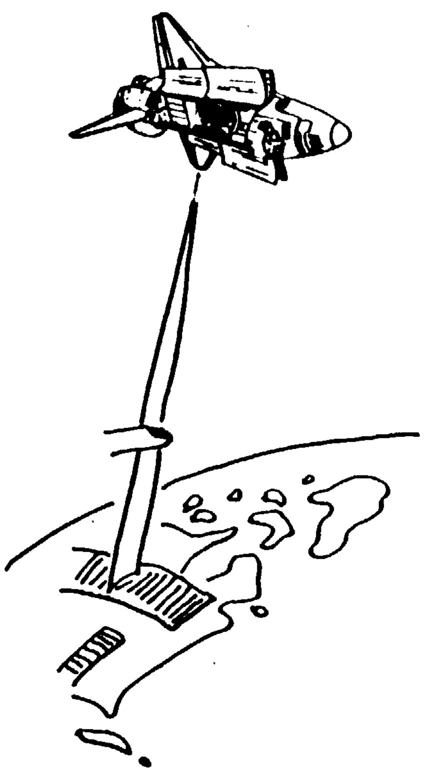
THE POTENTIAL TO EXTRACT ELEVATION VALUES FROM SAR DATA HINGES UPON THE AVAILABILITY OF DATA FROM SUITABLE MULTI-INCIDENT ANGLES VIEWS

The ability to ascertain relative elevation from SAR data is also limited to regions where suitable data of overlapping views from different angles exist. In regions with gradual topography two overlapping views from opposite sides may suffice. In regions of severe elevation changes, three or more looks may be required. Laprade[4] and Rosenfield[5] have postulated the optimum incident view angles on the assumption that binocular vision for perceiving stereo would be used to extract topography. The research indicates that opposite side views at the same angle (approximately 45 degrees) from the same altitude is optimum. These optimum view analyses are based on the assumption that the retinal disparity angle of features viewed under a stereoscope must be at least 3 degrees to perceive relief. These conclusions are not necessarily valid for an all analytic radar topography solution. In fact, regions with severe slopes will exhibit complementary shadowing due to the fact that the radar platform also provides the illumination. The opposite side views will only yield a single image which serves to fill in all the shadows. It may well be that the input needs of an analytic radargraphic system is best served with data obtained from four looks (two from each side).This data would resolve the layover ambiguity (or complementary shadowing)encountered in steep terrain. Also there is no reason to assume that opposite side views must be viewed at the same incidence angle and altitude to produce the best results.

SIR-B is the first space borne system with the built in flexibility to easily view the same area for a set of different view angles. SIR-C and SIR-D will have similar capability. We have very little knowledge of the later missions since they are in the definition phase. It is timely to perform the research suggested in this program outline so that the consideration can be given to the needs of the topography effort. VRM will present a spectrum of view angles that varies according to latitude. Table 2 shows the look angles expected for the mission set. We also show the estimated area coverage at different angles of incidence. Table 2 does not attempt to show where radar terrain views from one mission can be matched with terrain views at different view angles from a different mission. Combining data sets at different angles of incidences from different missions may provide the best opportunity for selecting suitable stereographic data for topography purposes.

SHUTTLE ACTIVE MICROWAVE EXPERIMENT (SIR-B) FOR
LARGE AREA TESTS (84)

SIR-B



- ANTENNA: MICROSTRIP PLANAR ARRAY, BI-FOLD AND MECHANICAL TILT, 10.7 x 2.2 METERS (L-BAND)
- CONSTANT ANGLE ILLUMINATION OVER 50 KM SWATH
- SELECTABLE INCIDENCE ANGLE
- FREQUENCIES: L-BAND (1.275 GHz)
- POLARIZATIONS: HH (L-BAND)
- RESOLUTIONS: 30M, 10M
- SWATH WIDTH: 30 KM TO 120 KM
- DATA RATE 46 MBPS
- DATA PROCESSING: DIGITAL, GROUND BASED AT JPL
- MULTI-INCIDENCE DATA: 10-60 DEG
- MISSION DURATION 25 HOURS - 6 HOURS OF WHICH WILL HAVE MULTI-INCIDENT ANGLE DATA

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We must also keep in mind that topography determination is not the primary driver for the NASA SAR missions and the system will have to function with the set of multi-view data that will happen irrespective of any topographic mapping requirements.

MISSION SUMMARY

The following provides a mission summary of the experiments that will provide the input data for the "Radargraphics System". The mission plans are in the definition phase and will be refined as each mission date approaches. .The earlier missions are of course the most defined,Table 2 shows the pertinant data parameters for the planned missions.

2.1 SIR-B (mid 84)

SIR-B will be the first space imaging radar mission which will provide quantitative, calibrated, multiple incidence angle imagery. SIR-B will also provide digital data which we feel is essential for producing topography from radar data. This contrasts to the SIR-A mission which collected analogue data (film) only. The Seasat mission provided digital data, however, the view incidence was near normal and the radar system itself did not have the system performance of SIR-B. While SIR-A and Seasat both had fixed viewing incident angles (47 and 20 degrees respectively), SIR-B will have the capability to acquire L-band imagery of the Earth's surface at selectable incidence angles ranging from 15 to 60 degrees from nadir. In addition the systems additions include a radiometric calibration capability which will provide a first order estimation of the absolute backscatter coeficients. To accomodate the variable incidence angles, the SIR-B has the capability to vary the PRF and receiver gain to compensate for the range of returned energy at different view angles. One of the announced objectives of the SIR-B mission is to determine the optimum radar illumination angles of incidence for stereoscopic observations of surface topography. In addition there is the mission potential to maneuver the Shuttle to obtain the opposite side imaging mode. Finally, range resolution has been improved by an increase in the pulse chirp bandwidth to 12 MHZ which will halve the range resolution cell from SIR-A.

The SIR-B will be operational for 25 hours with a digital data output rate of 48 Mbs. Six hours of this data should be suitable for stereo or topography interpretation. If we assume a ten percent of the data is lost to gaps in the TDRSS link, about 9500 giga-bits of SIR-B data can be processed for topography.

2.2 SIR-C (Mid 86)

The SIR-C mission will employ a combined L and C band antenna. The C-band portion of the antenna will receive in both horizontal and vertical polarizations . The antenna itself will be extended to about 12 meters in length with the C-band radar occupying one edge of the antenna. In addition the antenna microstrip panels are mounted on a new rigid strut assembly that will provide a flatter and more accurately pointed antenna surface. The longer length L-band antenna will provide an increase in gain. Floating point digital data hardware will provide a 5 bit mantissa plus an exponent which will greatly enhance the dynamic range potential of the uncorrelated data.

There is also the possibility that SIR-C will employ an onboard Shuttle data collection system that potentially could double or triple the amount of data returned from this mission. The current SIR-C data rate is limited by the 48 Mbs (megabits per second) Orbiter-to-TDRS ground link which is again reduced by the gaps in the Orbiter-to-TDRS coverage. The radar system itself has the capacity to produce data at four times this rate. Newly emerging recording technology such as the optical disk drive system could record 48 Mbs and store the data on board on a very compact format. One 1/2" x 15" x 15" optical disk will currently hold 4.5 giga-bytes and would be easily and quickly loaded by the Shuttle astronauts using a cartridge load device. A ten gigi-byte device on a 14 inch platter has been demonstrated and most certainly would be available in the 1986 time frame.

2.3 SIR-D AND SIR-E (87_89)

Current NASA plans call for a Shuttle/SIR-x flight about once a year beginning with SIR-C in 1986. There is very little specific information available about the mission plans for these later flights. We expect them to be about the same duration (25) hours as SIR-B. We expect that an X-band radar will be added to the planned C-band and L-band radar system. We would also expect that a far field antenna pattern measurement will be made on the total antenna assembly. This will enhance the calibration of the total system. The analysis of SIR-B and SIR-C data will provide a better understanding of the optimum illumination angles of incidence for topography determination. Since the radar characteristics for these missions are similar to SIR-B and SIR-C, these missions will have to opportunity to obtain the data to compt

VRM MISSION 88
MAPPING PHASE

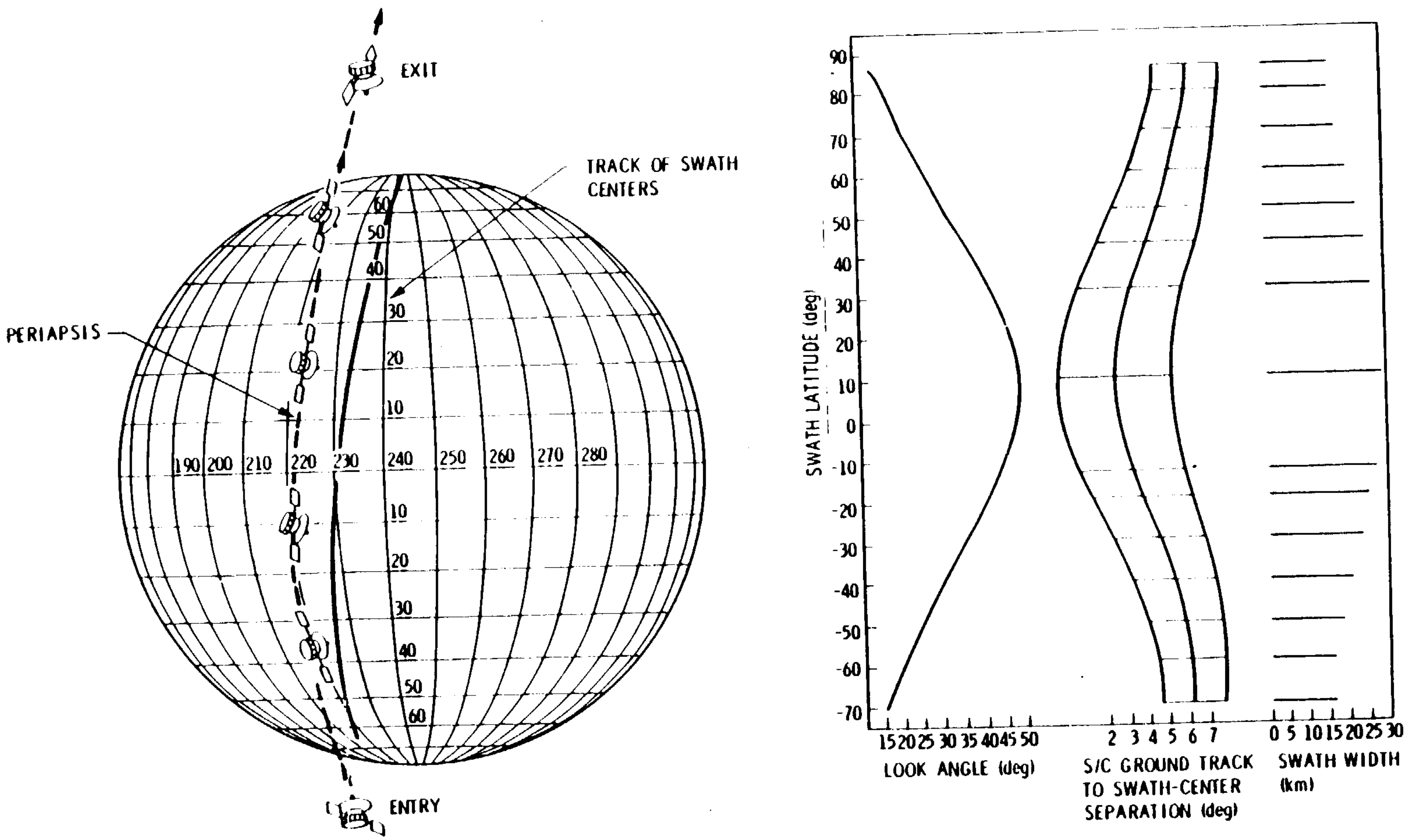


FIGURE 2.1

2.4 Venus Radar Mapper (VRM)

The primary objective of the proposed VRM mission is to obtain relative high resolution imaging of the entire surface of Venus. The Venus Radar Mapper vehicle orbit will be non circular. This will cause the size of the resolution cells to vary substantially. The resolution cell area will vary from about 300 meters to about 600 meters. The radar swath width will vary from about 19 kilometers to 29 kilometers. The radar illumination incidence angle will vary from about 20 degrees of nadir to about 50 degrees off nadir. Figure 2.1, is provided by the Jet Propulsion Laboratory, shows that mapping parameters as a function of spacecraft latitude.

At high latitudes, the large overlapping swaths will provide some over lapping same side views at slightly different incident angles. When Venus makes one inertial rotation on its axis (about 8 months), the radar will begin viewing the same areas from the opposite side at approximately the same incidence angle. If data collection can be extended beyond the nominal 8th month mission period, there will be an opportunity to employ the "Radargraphic System" to extract Venus topography.

Venus radar image data will be transmitted back to the earth at a rate of 1.46 giga-bits per VRM orbit. The VRM orbit is about 3.1 to 3.7 hours. In about 8 months the entire planet surface will have been in view of the radar system once. This translates to 2300 giga-bits of information. An extended mission could double the amount of data to be processed through the "Radargraphic System".

3. FUNCTIONAL HARDWARE REQUIREMENTS FOR THE RADARGRAPHIC SYSTEM

In Appendix A we have outlined what is, in our judgment, the three most promising methods to extract topography from SAR data. They are: 1) Direct processing stereo photogrammetry methods, (2) The interferometry method, and (3) The radar holography concept. The method selected will of course affect the make-up of the system hardware ultimately selected There are some similiarities in all three methods, however. There is the general requirement to extract multiview SAR images from the SAR data base, register the images pixel by pixel, and solve for the pixel location in three dimensional space. The final product, the three dimensional data matrix for the registered pixel set, would be written out to some some type of permanent medium. The data would be Xi(longitude), Yi(latitude), and Zi(radius from earth center). In one current view of the system, the SAR image pixels would be resampled (re-registered) onto a uniform latitude and longitude grid. Then an annotated Zi matrix with annotation specifing the center location and grid spacing would be saved. We suggest that the government laboratories (USGS and JPL) are already equipped with state-of= the art contour plotters and adding this capability to the "Radargraphics System" is redundant. The digital elevation data however, should be on a medium that is easily transportable to the plotting computer.

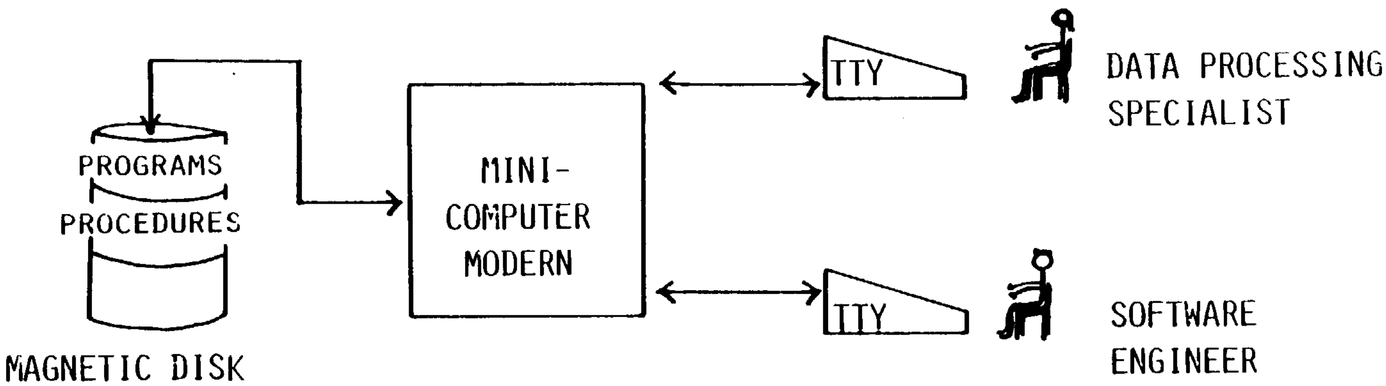
There are some stiff system hardware challenges that the ultimate system hardware must meet: (1) It should have an on line data base large enough to contain several of the required multi-view image sets. The task of searching out these images should not preempt or compete for bandwidth with the processing functions. The multi view images should be queued up in advance by separate processors. (2) It should have a multi or parallel bus structure that can be flexibly connected to parallel asynchronous processors. The system should be adaptable to easily add a processor or a mass storage unit to facilitate parallel processing wherever possible. (3) It should have a number of medium size high speed mass storage units to hold the intermediate image sets. The system should have the features for dynamically interconnecting these storage mediums to the processors so that the output from one processing step is immediately available as input to another. The interconnect should be such that the processor operating on the data has the total data flow bandwidth of that device for the duration of the processing step. (4) It should have special resampling hardware that keeps the image resampling task from bottlenecking the operation. (5) It should probably have some window into the system providing the data analyst with a view of the reconstructed images.(6) It will probably have an array processor connected to the computer most heavily involved with large matrix calculations.

THE OPTIMUM SYSTEM SHOULD BE A COMPLEX OF INTERCONNECTED COMPUTER PROCESSORS AND COMPUTER PERIPHERAL SYSTEMS

One system concept that shows promise for meeting the throughput requirements of the "Radargraphics System" is "the clustered computer" system complex. This approach is one of recent mini- and micro-computer system innovations for achieving a high volumn data thouchput in parallel with intensive parallel arithmetic operations with reasonable investments in computer equipment. Two other advanced concepts that provide these general system capabilities were examined. These were :(1) a system of "function-to-function" processors being promoted by Texas Instruments for their advanced microprocessor elements, and (2) the "attached processor" scheme being promoted by the Intel corporation for their advanced 32 bit microprocessor family. The "function-to-function" system is comprised of a complex of independent advanced microprocessors interconnected with specially adapted micro-processors that arbitrate the buss shared memory segments and facilitate the block transfer of data blocks from processor to processor. The "attached processor" scheme has a supervisor processor prompting other processors that have common data paths to selected portions of shared memory. The supervisor processor also arbitrates the data bus path to memory and controls when a processor can access an I/O channel.

The "clustered computer " complex hardware complement would be more costly than the above two approaches but would provide some major advantages. These are: (1) Software development can proceed on existing VAX-type systems already in existence at contractor and government laboratories which are likely to participate in the development and use of the "Radargraphics System",. (2)The system can evolve simply and systematically from a single CPU based system to the multi-CPU system shown in Figure 3.6. Whenever a processing task begins to monopolize an appreciable fraction of the core CPU, another processor could be added to the computer interconnect bus and dedicated to that task. (3) This systems approach can utilize modified versions of current operating systems. We anticipate that proven and reliable operating systems will be available for this system. (4) This clustered system will make it convenient to develop a special hardware interface independently for later integration into the system. For example, the forthcoming Vax-on-a-board would be an ideal driver for the image hardware re-sampling unit. The special purpose hardware, including the computer driver board, could be developed independently using an existing facility computer and a "Dec Net" interface for inputing the driver programs. This subsystem is integrated into the system with comparative ease by attaching the CPU board to the CI(computer interface) bus. The eminent release of VAX CPU components, vastly reduced in size and cost, make the clustered cumputer concept economically viable.

CORE ELEMENT OF RADARGRAPHIC SYSTEM IS A COMPUTER



CENTRAL ELEMENT OF RADARGRAPHICS SYSTEM IS STATE-OF-THE-ART MINI-COMPUTER -- NICE AND FRIENDLY -- TALKS TO MORE THAN ONE SOFTWARE ENGINEER -- HAS HIGH SPEED DISK SYSTEM

- USED TO DEVELOP THE PROGRAMS
- USED TO DEVELOP AND IMPLEMENT OPERATING PROCEDURES
- THIS COMPUTER SUPERVISES THE OTHER COMPUTER ELEMENTS

FIGURE 3.1

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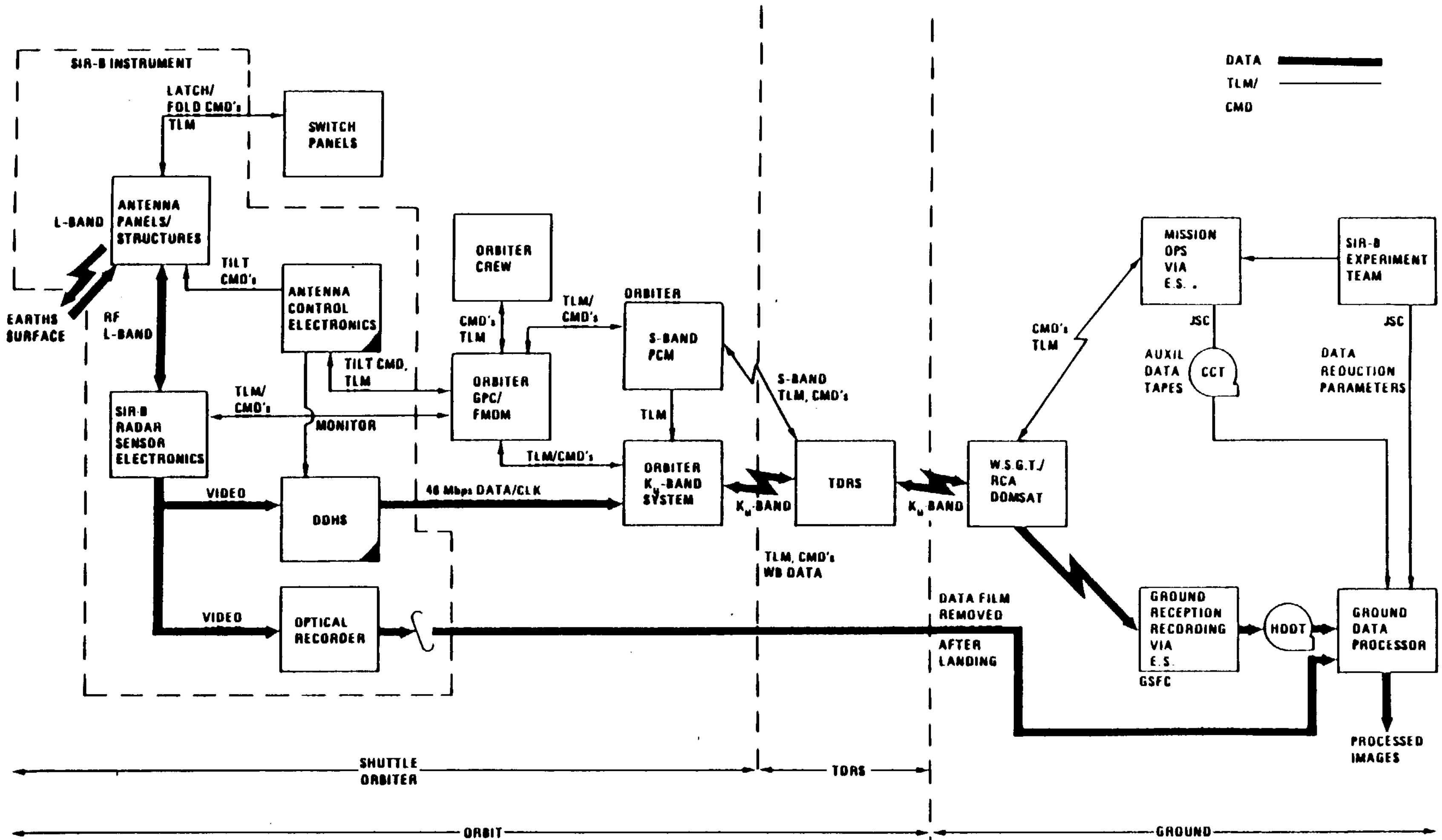
While the first software development should and probably will be developed on existing main batch share main frames,it makes sense to procure the core element computer soon after the Phase II effort is complete. Computer CPU time charges on current in-place VAX computers are likely to tax the budget of the "Radargraphic System" development program. Forthcoming systems will provide the equivalent throughput on much less expensive machines. Also it will be important to begin benchmarking the major arithmetic operations unencumbered by an all encompassing batch/timeshare operating system supporting parallel users. (The casual user would be appalled at the amount of the CPU resource that is squandered on managing a multi-use environment.) When the functional processing time budgets become known the programs could then migrate to the distributed processors as they are added to the system.

A computer driving the plotter could conceivably be part of the complex even though the plotting software and plotter interface has probably already been developed. Tying the plotting computer into this complex would provide an efficient means of transporting the data from the "Radargraphics System" data output file to the plotter input file. Each of the processing functions described below can be thought of as being performed using its own independent computer. The CPU's tied into the clustered computer still retain their UNIBUS features. This allows retention of current peripheral equipment developed around this interface.

SAR DATA PROCESSING BEFORE IT ENTERS THE "RADARGRAPHICS SYSTEM"

We will now discuss the system concept overview. We will begin by following the flow of the data through the system. The block diagram showing the operations on the data before it reaches the "Radargraphics System" is shown in Figure 3.2. This is an overview of the SIR-B flight and ground digital data handling subsystems. The new elements of the system are the digital recording and transmission components. Data is transmitted to the Tracking and Data Relay Satellite System (TDRSS), from the TDRSS to the ground station at White Sands, N.M., from there to GSFC via the RCA domsat link, and recorded at GSFC upon the High Density Data Tapes(HDDT's) for non-real time delivery to JPL. At JPL, the new digital correlator converts the raw SAR data from the HDDT's into imagery frames. The two-dimensional digital correlation process utilizes the Fast Fourier Transform (FFT) approach and will create a 100 kilometer by 60 kilometer pixel matrix in 1/500ths of real time. The processed digital image frame will be comprised of about 16 megabytes of 8 bit pixels.



NOTE: ◪ DENOTES NEW SYSTEM ELEMENTS

FIGURE 3.2

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COLLECTING THE OVERLAYING DATA SETS

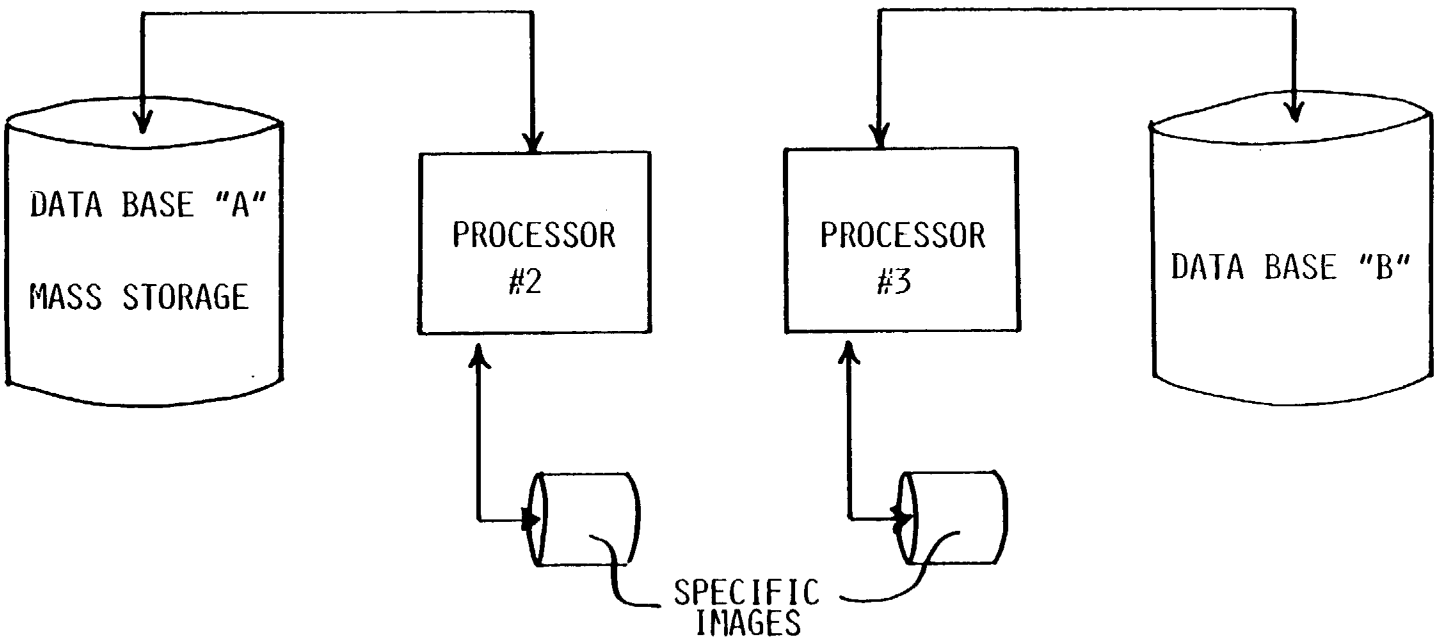
An obvious first step in the processing operation is to go into the data base and collect the two or more image frames of data that overlay the area of interest. BASD views this step as a major task considering the tremendous data base that will be created from the various SAR missions. To often we neglect the plight of the poor grunt back in the computer lab who has been handed the impossible task managing staggering volumns of data to handle with conventional equipment. This task can bottleneck the system operation as surely as any of the other major subtasks identified below.

On SIR-B we can expect 1.2×10^{11} bytes of data of multi-incident angle view data alone. This will require about 2200 reels of magnetic tape containing a little over 6000 image frames. We expect the number of multi-incident angle view frames to increase by a factor of 5 with the SIR-C mission. The SIR-D mission could easily double the amount of multi-view data sets. Additional problems are caused by the fact that the cross track direction in one image does not necessarily align with the cross track direction in the second alternate view image frame. This may require the system to collect several frames from each mission set to consolidate the contrasting view sets of the same area.

Our system concept shown in Figure 3.3 shows a separate processor searching out the desired image frame. Sub-portions of the data base is first copied onto a large mass storage device. (A 25 giga-byte device would not be too large for this function.) The frame searching processor then transfers a specific image frame to a smaller, faster device . A 30 megabyte Winchester disk would be about right for this task. One small drive should be provided for each image frame being processed for elevation . The processor involved in the transfer between mass storage units need not be large or expensive. It may even reside in the next generation of computer disk drive controllers.

In the summer of 1983, officials from NASA and JPL will have the first in a series of meetings aimed at setting up an optical disk drive system on the VAX 11/780 at JPL to begin archiving Voyager data on optical disk media. We think that the economics of optical media vs. magnetic tape media will drive the SIR-x operations into using optical media for outputting the mission data. One 80 dollar optical disk will hold the equivalent of 40 6020 bpi 2400 ft. reels of tape. This bodes well for the "Radargraphics System" since it provides a data base with a much higher input speed in a more compact format, along with the advantages of random access.

SYSTEM ELEMENTS TO SEARCH OUT THE MULTI-VIEW IMAGE AREAS



- LOCATES IMAGE PIXELS FOR SPECIFIC AREAS
- SYMBOINT PROCESSORS

FIGURE 3.3

RESAMPLING OR REREGISTERING THE IMAGES

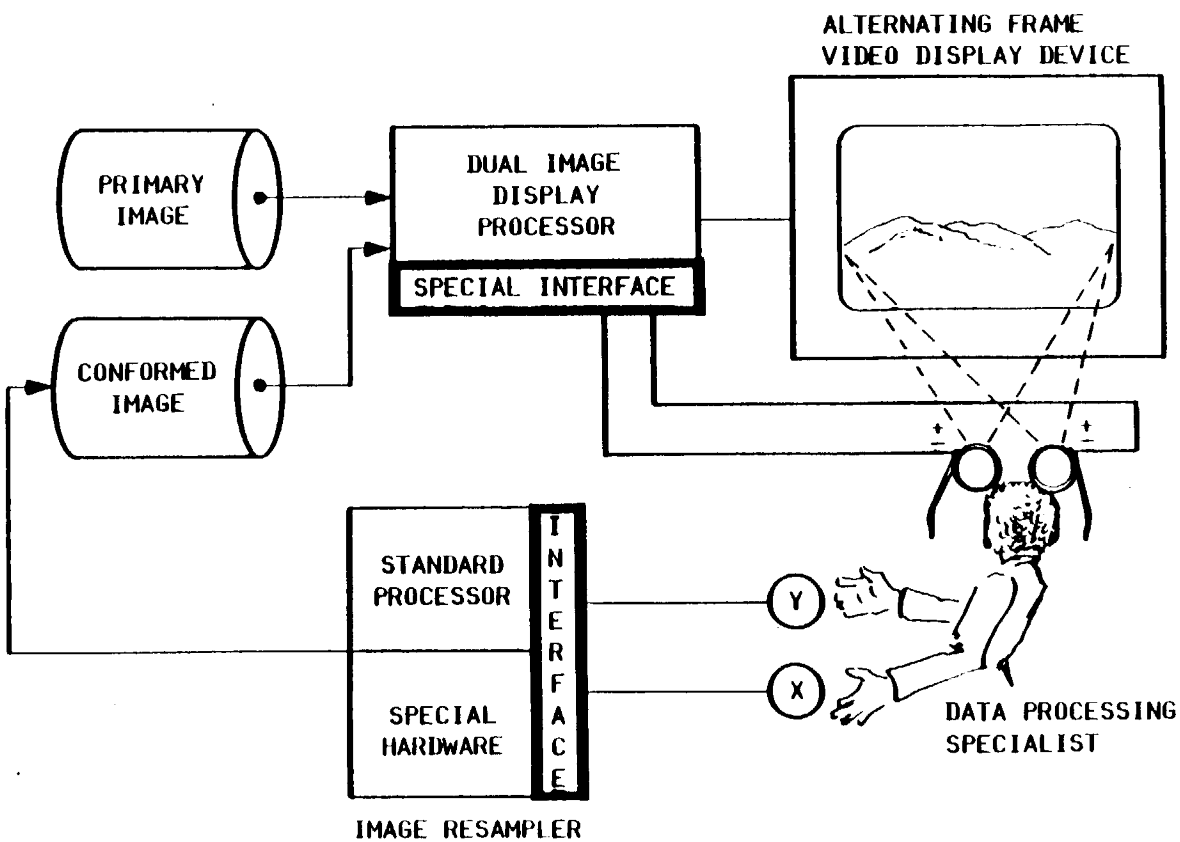
After reviewing the available methods for obtaining elevation,we feel that it will be difficult to avoid resampling the image frames at some point in the operation. Figure 3.4 illustrates our system concept for performing this function . The diagram show this function coupled with human intervention. Each image frame would reside on a separate disk. A dedicated processor will alternately transfer the image frames from the high speed mass storage device to a video display unit. A special pair of eye glass lenses will be alternately darkened in sync with the alternating frames. A separate and independent hardware resampler will re-register the image data on one of the disk units in near real time. The resampling coefficients will be iteratively modified from an X-Y input device, giving the operator the capability of coaligning specific features in the data set. Features such as road intersections or a specular reflector, like a river or a lake, could provide the tie points in the data set. The resampling processor always goes back to the orginal data set so that no data set is resampled more than once. Appendix B provides a discussion of the resampling operations.

We are painfully aware of the need to tie down the method for solving the elevation data to understand where image resampling fits into the operation. We are convinced that it will be a necessary operation even if the elevation algorithms are invoked prior to the the first image resampling .It may be that the final image registration is done just prior to final data output. The system we have shown makes use of the human's elegant servo mechanism for focusing details. A system like the concept shown above provides a window into data processing junctures and would be invaluable to the initial evaluation of the processing operation.

SOLVING FOR ELEVATION TOPOGRAPHY

Figure 3.5 shows the processor involved in the solution of elevation detail. The input to the processor are two or more "prepared" data files on separate mass storage devices. The manner in which the data is prepared is contingent upon the method selected for the final elevation solution. The three different methods alluded to in Appendix A all require a sizable amount of CPU processing time. We visualize a dedicated high performance mini computer based processor augmented by an array processor for this operation. The final output will be a three-dimensional array of data locating individual pixels in three-dimensional space. As stated earlier, the final output data array may be reduced to one Zi array through proper resampling so that Xi and Yi are implied.

SYSTEM ELEMENTS TO REGISTER IMAGES



A/N 3196

FIGURE 3.4

9950-947

PROCESSOR FOR DETERMINING ELEVATION TOPOGRAPHY

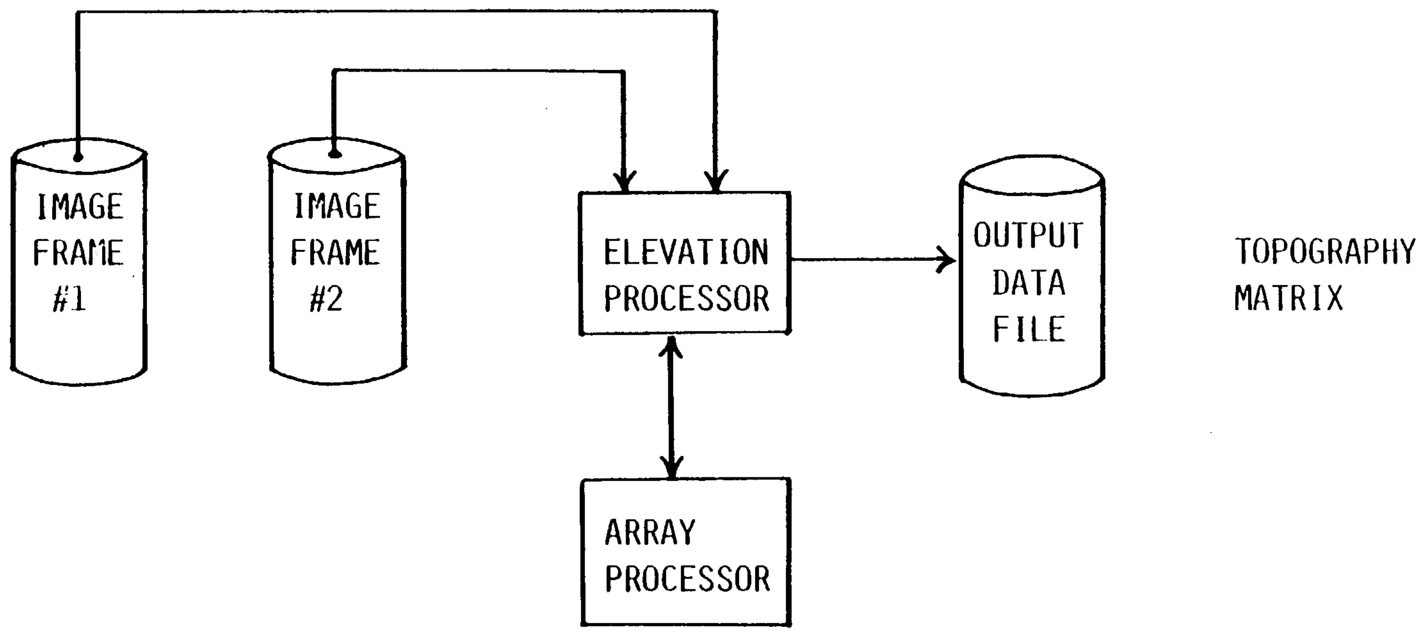
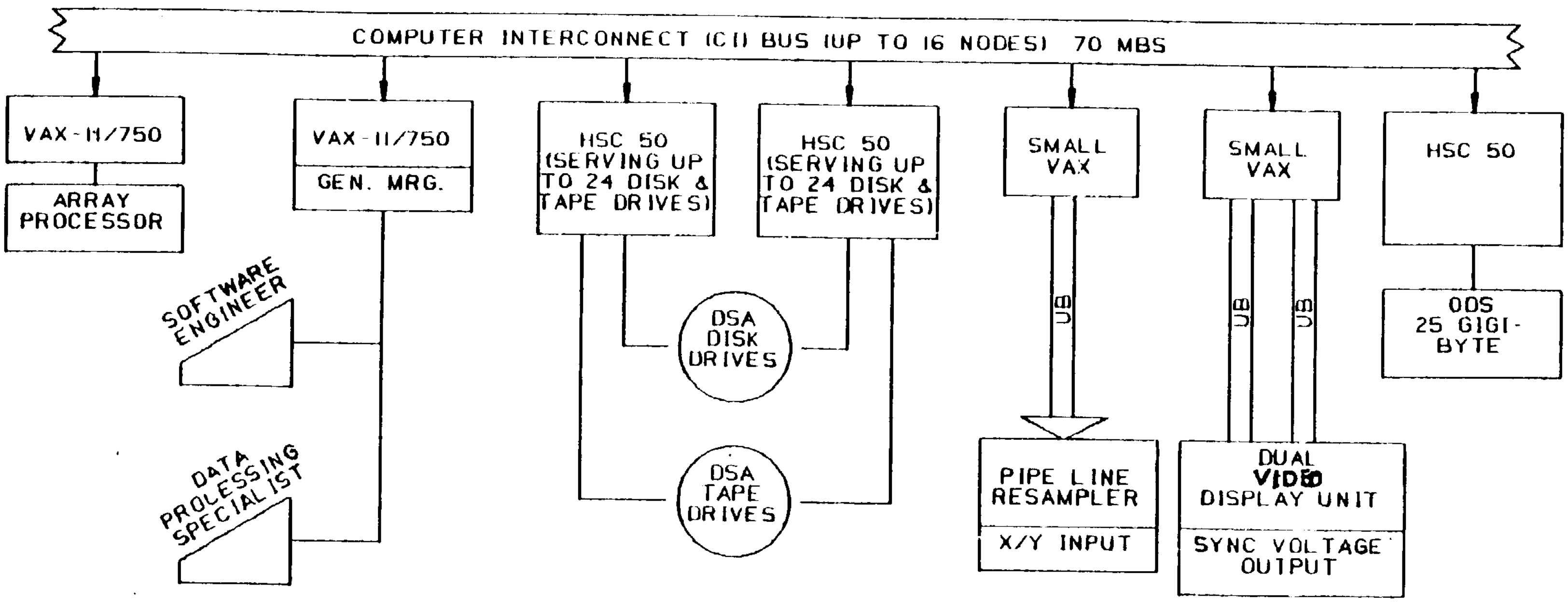


FIGURE 3.5

9950-947

RADAR GRAPHIC SYSTEM CLUSTERED PROCESSORS



- BEGIN DEVELOPMENT WITH INHOUSE HARDWARE
- UN BURDENS OPERATING SYSTEM
- FLEXIBILITY, EXPANDABILITY

Figure 3.6

9950-947

SYSTEM ARCHITECTURE CONCEPTS FOR A RADARGRAPHIC SYSTEM

An objective of this study was to conceptualize a complement of hardware and software that would perform the functions outlined for the "Radargraphics System". It was felt that this exercise would be helpful to arrive at a preliminary estimate of the eventual cost of the system. Figure 3.6 illustrates our concept of clustered computers associated with specially adapted hardware. Our conceptual approach is simple . It involves distributing the CPU intensive tasks to as many uniquely dedicated processors as required to achieve the desired throughput. It also dictates that any specialized hardware subsystems contain their own dedicated processors . The embedded CPUs in the special subsystems such as the "Pipeline Resampler" and the "Dual Video Display Unit" are examples of the later. The new high performance HSC 50 mass storage device controller is in fact a specal adaptation of a high performance dedicated processor.

This conceptual approach is a reflection of the nlightened voices in the computer industry echoing their vision of the trends of the future. All this is possible because of the tremendous economies of scale brought on by advances in VLSI computer component manufacture.

4 PROGRAM PLAN AND SCHEDULE

The singular urgent facet of the "Radargraphics Development" at this juncture is to focus on and identify the best method for deriving topography from the multiple-view SAR data. This was anticipated from the early planning stages of this program. Figure 4-1 shows a planning chart developed at the beginning of the Phase I study effort. The chart shows the Phase I effort ending with the bubble identifying the final Phase I oral presentation at the USGS in Reston Va. on April 1, 1983. This report is a summary of that presentation.

The next funded effort indicated on the planning chart in Figure 4-1 is the Phase II effort beginning in fiscal 84. This effort is to identify and test a software solution for determining topography from SAR data. (Note the bold letters on the first line extending from the Phase II block identifier.) Phase II would be accomplished without any hardware procurement. It would be strictly the development of software programs for existing VAX 11/780 computers at contractor and government facilities. However, we must constantly reflect on how the ultimate solution will effect the complement of dedicated hardware that needs to be procured in Phase III to provide the needed throughput.

Intervening between the Phase I and Phase II efforts is some independently efforts at BASD, various government agencies, and possibly other contractorsto gain more insight into the topographic solution.The various concepts will be presented in a "Method Workshop" at JPL in August 1983. Two items should come out of this workshop: (1) a better comparative understanding of the alternate methods for extracting elevation topography and (2) a statement of work for the Phase II activity.

If the Phase II effort provides conclusive proof that elevation topography can be derived from multi-look SAR data, then it would be prudent to proceed with the Phase III and Phase IV portion of the program. Phases III and IV consist of the hardware and software procurement of a system to produce radar topography on a large scale.

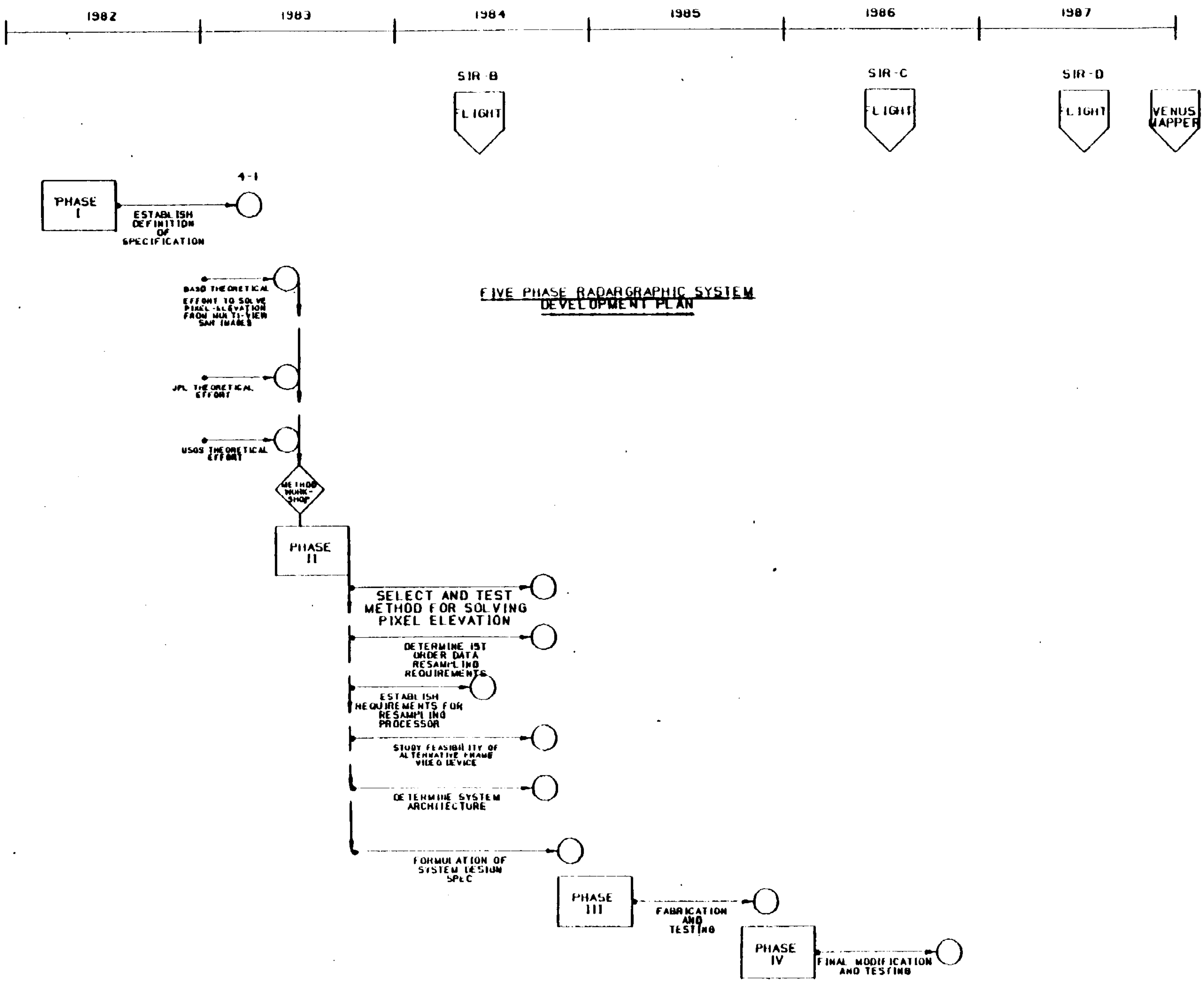


FIGURE 4-1

ORIGINAL PAGE IS OF POOR QUALITY

9950-947

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1. Sherman, W.U., "Laboratory Investigations at the USGS at Flagstaff using SLR Aircraft Imagery", Private Communications, 1981.

2. Sherman, W.U., "Presentation to the "Radar Graphics Committee" at the Jet Propulsion Laboratory", December 1981.

3. Elatchi, Charles, "Spaceborne Imaging Radar Probe 'in depth'", IEEE Spectrum, November 1982.

4. LaPrade, G.L., "An Analytical and Experimental Study of Stereo for Radar", Photogrammetric Engineering 29/2, March 1963, 294-300.

5. Rosenfield, G. H., "Stereo Radar Techniques", Photogrammetric Engineering, Vol. 34, No. 6-1968.

APPENDIX A

A preliminary investigation was made into the available methods for obtaining elevation information from Synthetic Aperture Radar data or images. The methods identified; direct processing, stereo photogrammetry methods, interferometry and a holography concept, were subjected to only a cursory study. The first of these methods have been well presented in the literature, and the latter are concepts which may warrant further study.

The first step in this study was a review of SAR signal processing functions and resulting images. A SAR is basically a high resolution radar system which uses a known platform motion to provide azimuth or along track resolution. Integration of the returned signals from a ground target is performed during the time the target is within the azimuth beamwidth. The resulting reduced data yields an azimuth resolution which is independent of range unlike the angular resolution of a standard radar system. The signal processing in azimuth has been presented in the literature as doppler beam shapeing, pulse integration and holography all yielding the same image structure. The range or across track resolution is performed by range gating or simply timing the returned signal. Pulse compression and matched filtering techniques are usually employed to improve the average power of the received pulse.

The resulting range and azimuth resolutions define a cylindrical coordinate system as shown in Figure 1. The radar is capable of accurately determining location of returns along track and in range but the processed data cannot distinguish the angular coordinate of the point on the cylinder, only that a given return most probably is within the elevation beamwidth of the antenna, θ_B in the figure which is centered at θ_d below the local horizontal. The SAR signal processing function employs assumptions about the nature of the ground surface to a priori define the third coordinate. These assumptions have the net result of positioning a return from an elevated point (P in the figure) onto the assumed ground surface (P^1 in the figure), using the measured range and azimuth locations. Considering this, the accuracy of the image is proportional to the accuracy of the assumed surface and, hence, contains no elevation information.

The properties of SAR images are summarized in Figure 2 and again in the equations of Figure 3. The implicit ground surface assumption is contained in the transfer functions of a point scatterer on the ground.

The first methods for elevation determination use the schematic of Figure 5. This two-dimensional picture (platform velocity vectors are normal to the paper) show two SARs imaging the same point located height h above the assumed surface. The two looks will place the point on the images separated by ΔP. After identifying this distance ΔP on the two images it can be used in a direct but iterative computation to produce an elevation as shown by Leberl.[1] The images may be subjected to a resampling or stretching and reorientation by which the amount of stretching locally may be used to yield elevation. Finally, the images themselves may be used in a stereo viewer to estimate elevation similar to photogrammetry methods.

A problem with each of these methods is that the stretch, ΔP, is a function of range implying a non-linear computation whose accuracy decreases with increased average range. A further problem inherent with these methods is the identification of an identical point on two or more images. Large differences in view angles (large platform separation) may cause reflected energy to be quite different from the same point. However, each of these methods has certain advantages, the first involves a simple computation which can be performed on a pixel cell basis. The second, image resampling technique can be used to "average" over the entire image and eliminate singular type errors. Local ground continuity conditions can be used to effectively filter the image. Finally, the "stereo viewer" concept can eliminate the digital processing and be used for quick, preliminary results. The methods are summarized in Figures 6, 7 and 8.

It is possible to obtain height directly from measurement of a single look if the angular resolution is present. This technique, called interferometry, is depicted in Figure 9. A pulse is transmitted from a single array and received by two antennas, one above the other. The phase difference is measured between the two receivers and used to determine the depression angle, θ_d,

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[1] Leberl, F. W., "Accuracy Aspects of Stereo Side-Looking Radar", JPL Publication 79-17, March 1, 1979.

of the target. This technique simply employs a large array to obtain elevation resolution. However, it may be possible to use a significantly smaller second array and use the received signal from the large array to match filter the received signal of the smaller array. This can effectively thin the second array, but the separation between the two antennas is determined by the resolution required. This method has a disadvantage that the increased hardware complexity is not planned for future SAR missions.

Finally, a concept is proposed which employs the extremely stable local oscillator in the SAR to record a partial hologram in the range dimension. The azimuth processing of the data has been shown to be equivalent to a one-dimensional hologram.[2] If several looks at the same ground can be made, it is believed a similar recording can be made in range.

An optical hologram is presented in Figure 11 where an object is illuminated by a source beam and scatters energy toward a recording medium or film. A reference beam which is coherent to the illuminated beam is also directed toward the medium and produces an interference pattern on the film. The recording intensity is proportional to the sum of intensities of the reference beam, the scattered beam and the interference pattern. Illuminating the exposed film with the reference beam yields a reconstructed image since all the information is contained in the interference pattern.

The radar concept is shown in Figure 12 where the movement of the SAR is transverse to the line connecting the three locations. The platform moves to the different locations in the figure by moving subsequent orbits or changing flight paths and flying past the target again. The radar carries its own illumination source and reference beam which are coherent due to their relation to the single Stable Local Oscillator (STALO). The interference between the reference and returned signal is provided by the mixing operation and recorded in amplitude and phase. Because of the high stability of the STALO and knowledge of the platform location, returns from subsequent

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[2] Maksimov, M.V. et. al., Radar Anti-Jamming Techniques, Pg. 356, Artech House, 1979.

orbits will be coherent. The result is believed to be analogous to linear samples of the entire recording aperture above the ground to be imaged. As listed in Figure 13, the principle differences between the optical hologram and the radar hologram is the frequency and the changing illumination angle. The difference in frequency is apparent in the fact that the recording medium cannot be used directly to obtain an optical image. The changing illumination can cause varying shadows and scattering. It is believed that digital processing using the known platform location can eliminate both problems. The amplitude and phase of the returns will be used to produce the image resolution in a fashion similar to interferometry. In fact, the phase data and platform location can be used to implement interferometry if identical points on the two images can be found. The potential advantages of holography include resolution independent of range and no requirement to identify identical points.

Figure 14 lists the salient features of all the methods proposed.

GEOMETRY OF A SYNTHETIC APERTURE RADAR

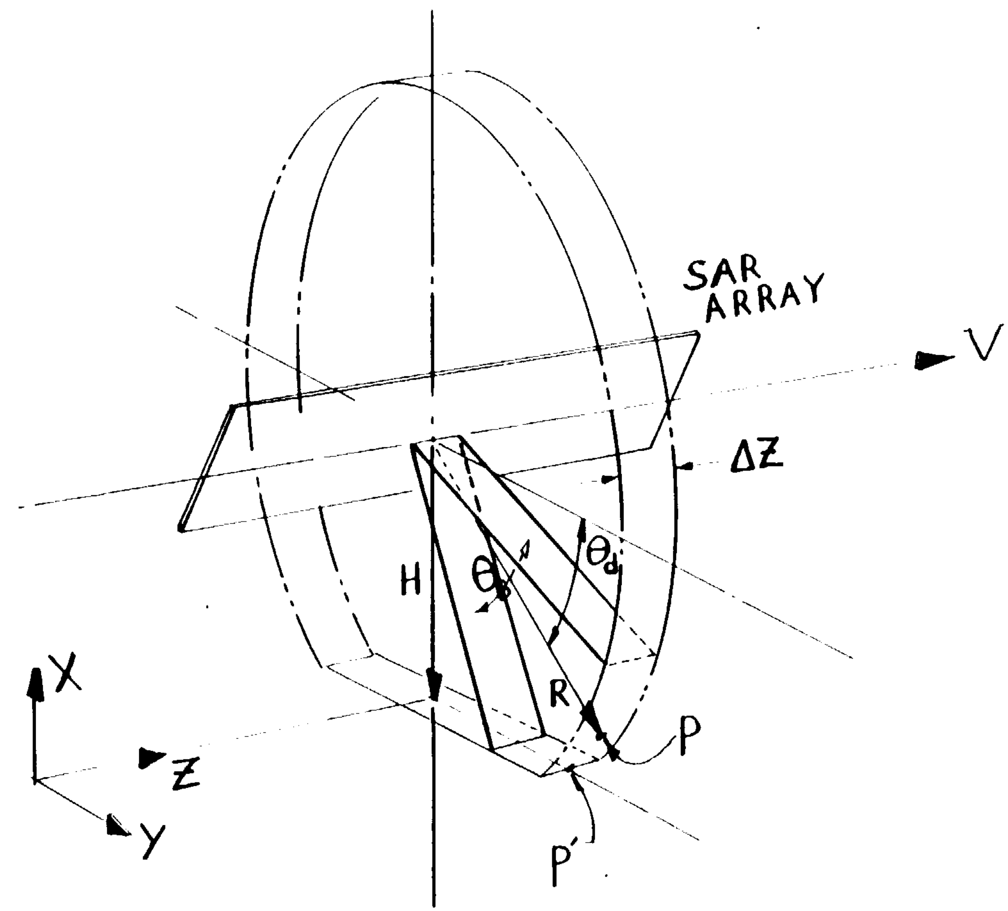

FIGURE 1

PROPERTIES OF SAR DATA

- AZIMUTH RESOLUTION INDEPENDENT OF RANGE (TRUE LENGTH RATHER THAN ANGULAR RESOLUTION)

- COORDINATE SYSTEM OF PROCESSED DATA IS: Z - AZIMUTH
  T - RANGE

- DATA PROCESSING NEEDS:
  - GROSS GEOMETRY OF SURFACE (MEAN CURVATURE)
  - VELOCITY OF SURFACE (PLATFORM MOTION AND EARTH ROTATION)
  - POSITION OF RADAR PLATFORM
  - SYSTEM TRANSFER FUNCTION (RADAR SYSTEM, ANTENNA PATTERN)

- RESULTING DATA ACCURACY IS PROPORTIONAL TO ACCURACY OF PLATFORM/ SURFACE GEOMETRY AND MOTION

FIGURE 2

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SYNTHETIC APERTURE RADAR

DATA REDUCTION (ELACHI, 1982)

$$\sigma(X,R) = \left[S\ (X,R)\ \otimes\ H_2^{-1}(X,R)\right]\ \otimes\ H_1^{-1}(X,R)$$

WHERE: $\sigma(X,R)$ IS CALCULATED REFECTIVITY PROFILE

S (X,R) IS RETURNED SIGNAL

$$H_2\ (X,R) = \frac{2}{CV}\quad \delta(X)\ A\ (R)\ EXP\ (-J\ \psi(R))$$

IS TRANSFER FUNCTION OF TRANSMITTED PULSE

$$H_1\ (X,R) = W\ (X)\ EXP\ [-J\ \frac{4\pi R_1(X)}{\lambda}\quad \delta(R-R_1\ (X))]$$

IS TRANSFER FUNCTION OF POINT TARGET ON GROUND

W(X) IS RADAR ILLUMINATION AT POINT TARGET

$R_1(X)$ IS RANGE TO POINT TARGET

FIGURE 3

9950-947

METHODS FOR ELEVATION DETERMINATION

- DIRECT PROCESSING OF MULTIPLE LOOKS
- INTERFEROMETRY WITH SINGLE LOOK
- HOLOGRAPHY WITH MULTIPLE LOOKS

FIGURE 4

TWO VIEW PROPOSAL

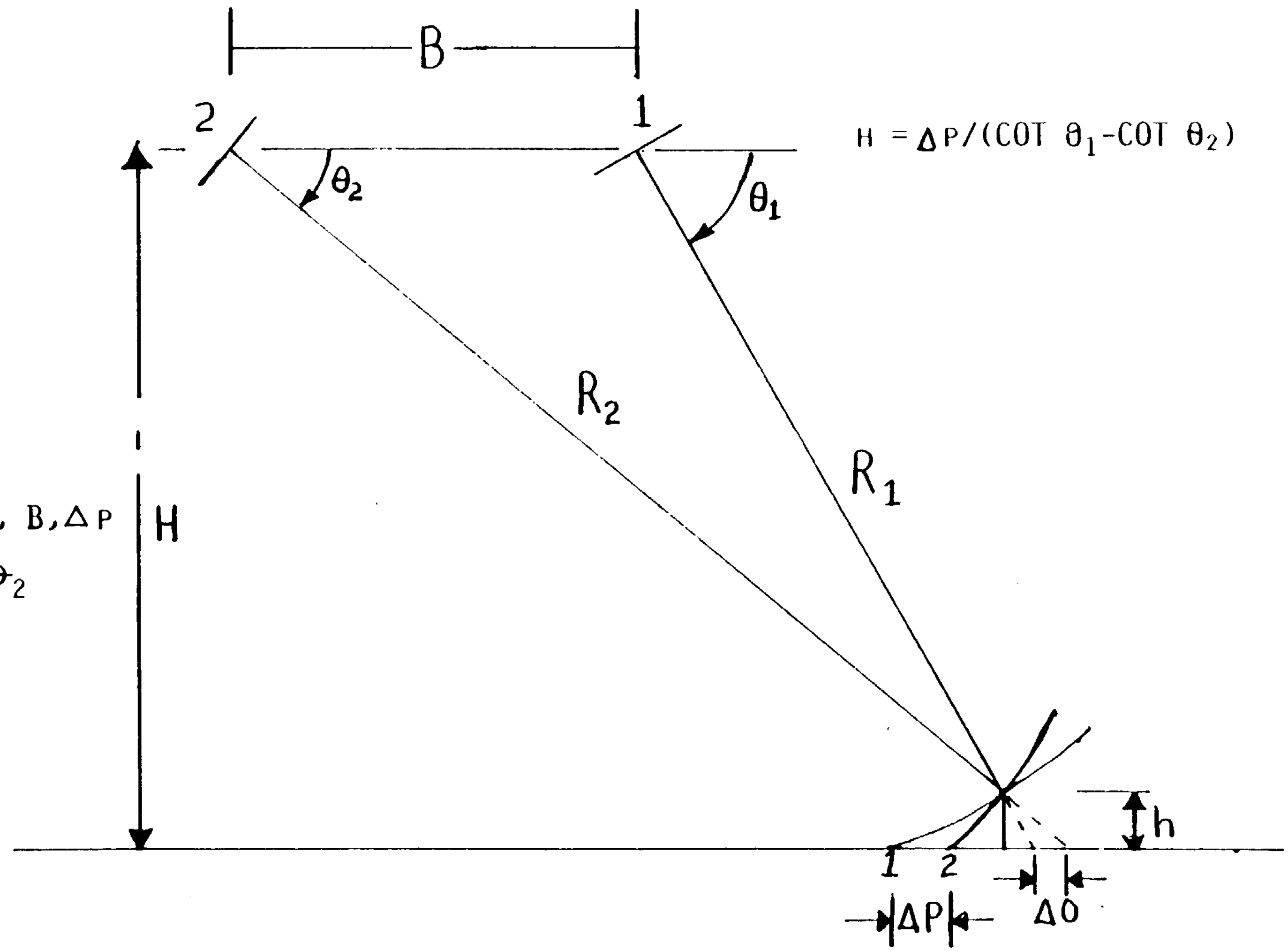


FIGURE 5

9950-947

STEREO RADARGRAMMETRY

- USE TWO "SAME SIDE" IMAGES (AVOIDS COMPLIMENTARY SHADOWING)
- APPLY PHOTOGRAMMETRY TECHNIQUES TO IMAGES
- ITERATIVE SOLUTION TO SOLVE FOR H

ADVANTAGES

- USE OF CURRENT SAR DATA (SEASAT, SIR-A, SIR-B, USGS)
- WELL UNDERSTOOD TECHNIQUE
- DIRECT COMPUTATION ON PIXEL CELL BASIS

DISADVANTAGES

- POSSIBLY SENSITIVE TO PLATFORM LOCATION AND RANGE ERRORS
- ACCURACY PROPORTIONAL TO RANGE FROM PLATFORM

FIGURE 6

USE OF TWO VIEW DATA FOR ELEVATION

(S.SAUNDERS, JPL)

1. REGISTER DATA TO ABSOLUTE REFERENCE (PLATFORM ATTITUDE INFORMATION)

2. ROTATE IMAGES TO ALIGN RANGE DIRECTIONS

3. IDENTIFY IDENTICAL RETURNS IN FRAMES 1 AND 2 (POINT P IN FIGURE)

4. STRETCH ONE FRAME TO OVERLAY IDENTICAL RETURNS

5. AMOUNT OF STRETCH (ΔP) PROPORTIONAL TO HEIGHT

ADVANTAGES:

- SMOOTHING OR FILTERING OF HEIGHT DATA POSSIBLE
- ENTIRE IMAGE PROCESSED

DISADVANTAGES:

- POTENTIAL ERROR CAUSED BY RESAMPLING
- RESOLUTION IS FUNCTION OF RANGE

FIGURE 8

DIRECT METHOD

(F. W. LEBERL)

- COMPUTE H FROM ΔP, RANGE DATA AND PLATFORM LOCATION DATA

ADVANTAGES

- SIMPLE COMPUTATIONS
- ONLY ONE IMAGE IS ROTATED AND STRETCHED (ALIGN RANGE DIMENSIONS)
- USE CURRENT SAR DATA (SEASAT, SIR-A, SIR-B, USGS)

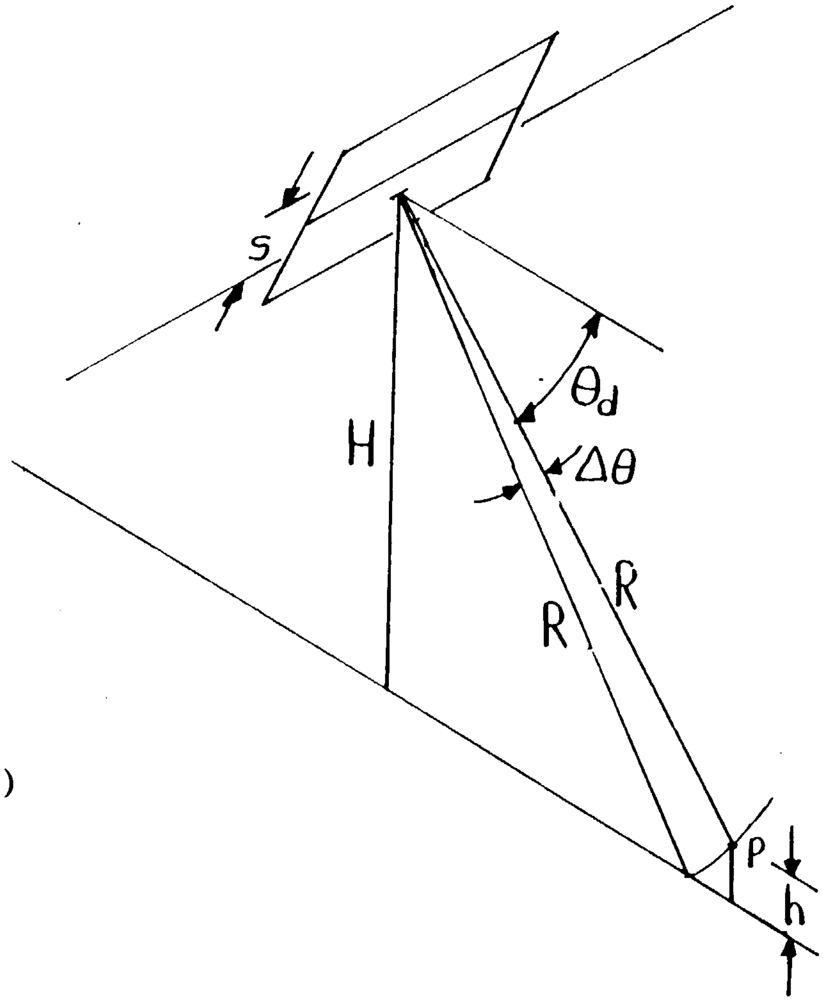
DISADVANTAGES

- POTENTIAL DIFFICULTY OF IDENTIFYING SUFFICIENT IDENTICAL IMAGE POINTS
- POTENTIAL ERROR CAUSED BY RESAMPLING
- HEIGHT RESOLUTION FUNCTION OF RANGE RESOLUTION AND RANGE (DEPRESSION ANGLE OF TARGET)

FIGURE 7

INTERFEROMETRY

(SINGLE LOOK)



$$\Delta\theta = \frac{h}{R \sin}$$

H = 285 KM

= 30.5 KM (100′)

30^0	$.009^0$
45^0	$.006^0$
60^0	$.005^0$

FIGURE 9

INTERFEROMETRY

- TRANSMIT ON SINGLE SAR ARRAY - RECEIVE ON TWO ARRAYS
- DETECT PHASE DIFFERENCE BETWEEN RECEIVED SIGNALS
- ESTIMATE ANGLE OF RETURN FROM PHASE
- FROM RANGE AND ANGLE, COMPUTE HEIGHT FROM ASSUMED SURFACE

ADVANTAGES:

- SINGLE DATA SET TO COMPUTE ELEVATION (ADD PHASE DATA)
- SIMPLE COMPUTATION

DISADVANTAGES:

- ANTENNA TWICE AS LARGE AS REQUIRED FOR SAR MISSION
- LOW ERROR TOLERANCES ON ANTENNA AND RECEIVING SYSTEM
- POSSIBLE ANGLE AMBIGUITIES WITH DECREASED HEIGHT RESOLUTION

FIGURE 10

SAR HOLOGRAPHY

(RANGE DIMENSION ONLY)

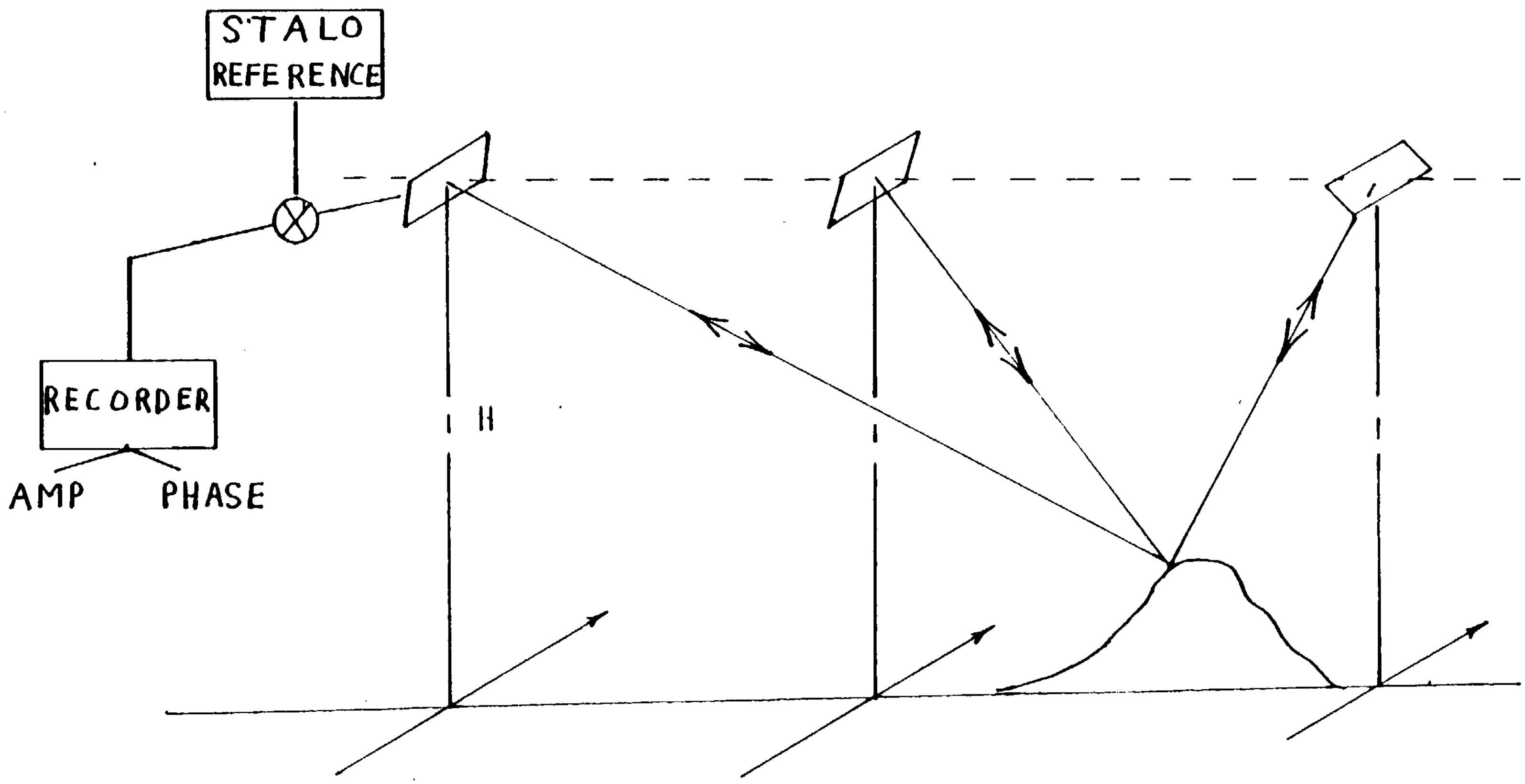
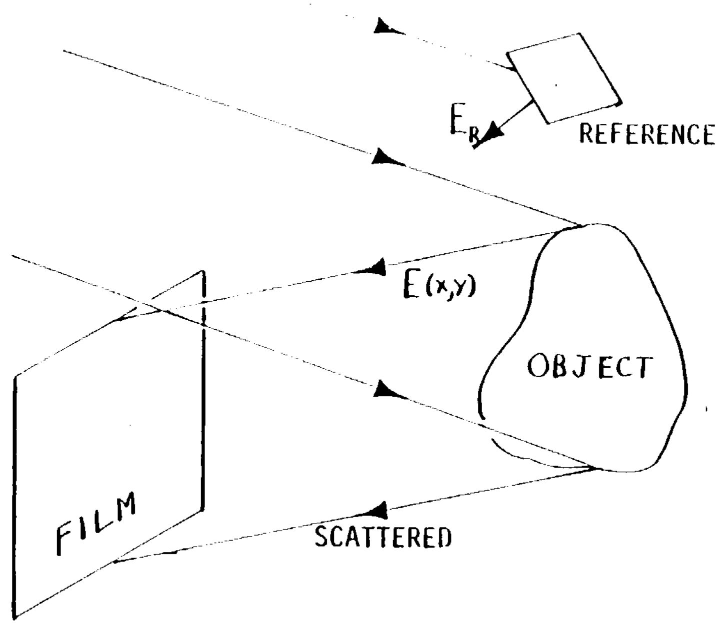


FIGURE 12

9950-947

OPTICAL HOLOGRAPHY



$$I\ (X,Y) = E_R^2 + E^2(X,Y) + E_R\ E(X,Y)\ \mathrm{EXP}\ [J\ (W_X X + \phi(X,\ Y))]$$

$\phi(X,Y)$ IS PHASE DIFFERENCE BETWEEN SCATTERED AND REFERENCE WAVE

$W_X = (2\pi / \lambda)\ \mathrm{SIN}\,\theta$ (θ IS ANGLE BETWEEN E_R AND E(X,Y))

FIGURE 11

COMPARISON OF OPTICAL AND RADAR HOLOGRAMS

OPTICAL	RADAR
EXTERNAL REFERENCE	INTERNAL REFERENCE
REFERENCE SPATIALLY AND TEMPORALLY COHERENT	REFERENCE TEMPORALLY COHERENT
ILLUMINATION FROM FIXED ANGLE	CHANGING ANGLE OF ILLUMINATION (VARYING SHADOWS)
CONTINUOUS APERTURE RECORDED	FEW LINE SAMPLES OF APERTURE
RECONSTRUCTED IMAGE VISUAL	RECONSTRUCTED IMAGE DIGITAL

FIGURE 13

9950-947

SUMMARY OF ELEVATION METHODS

PROBLEM: SAR DATA IS TWO DIMENSIONAL (AZIMUTH, RANGE)

DIRECT METHOD (TWO LOOKS)	SIMPLE CONCEPT - USE CURRENT SAR DESIGNS ACCURACY FUNCTION OF RANGE POTENTIAL DIFFICULTY IDENTIFYING POINTS
INTERFEROMETRY	SINGLE LOOK YIELDS ELEVATION SIGNIFICANT CHANGE IN CURRENT SAR DESIGN POSSIBLE AMBIGUITIES
RADAR HOLOGRAPHY CONCEPT	INDEPENDENT OF RANGE CURRENT SAR DATA NEEDS DEVELOPMENT

FIGURE 14

APPENDIX B

Copies of the Viewgraphs from the
Image Resampling Presentation at the
Radargraphic Phase I Oral Presentation

"The Science of Resampling Radar Images"

By Dr. Harold Reitsema, BASD

IMAGE PROCESSING APPLICATIONS FOR SAR

- TELEMETRY COMPRESSION
- DATA FORMATTING
- CONVERSION TO X, Y, Z COORDINATES
- IMAGE ANALYSIS

A/N 3185

9950-947

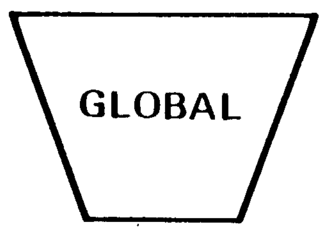
SAR RESAMPLING REQUIREMENTS

- PROVIDE UNIFORM PIXEL DIMENSIONS
- CO-REGISTER MULTIPLE LOOKS
- TRANSFORM TO MAP COORDINATES

A/N 3185

9950-947

DISTORTIONS WHICH ARE COMPENSATED FOR BY RESAMPLING



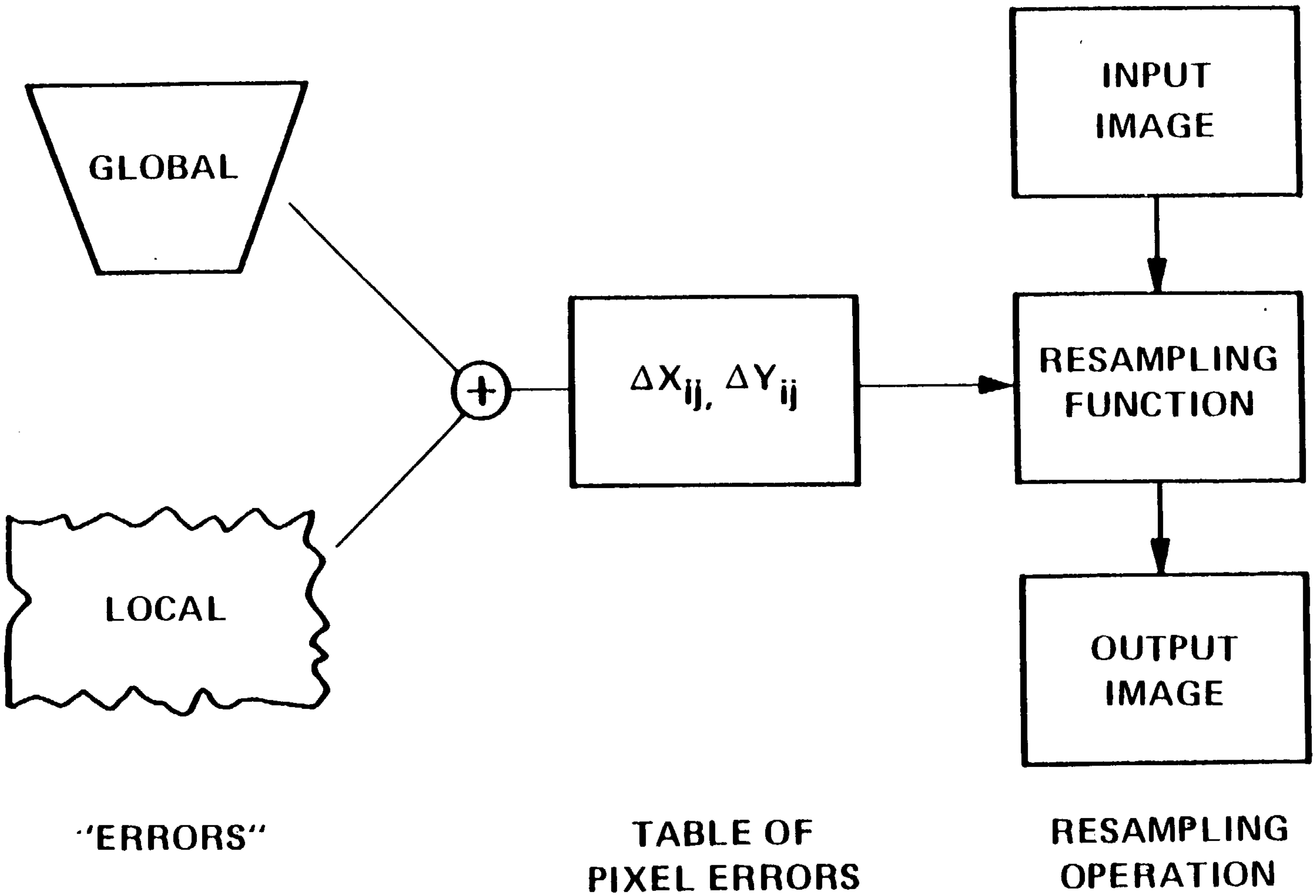
SCALE
TRANSLATION
ROTATION
KEYSTONE
COORDINATE PROJECTION

ELEVATION

A/N 3185

9950-947

RESAMPLING PROCEDURE



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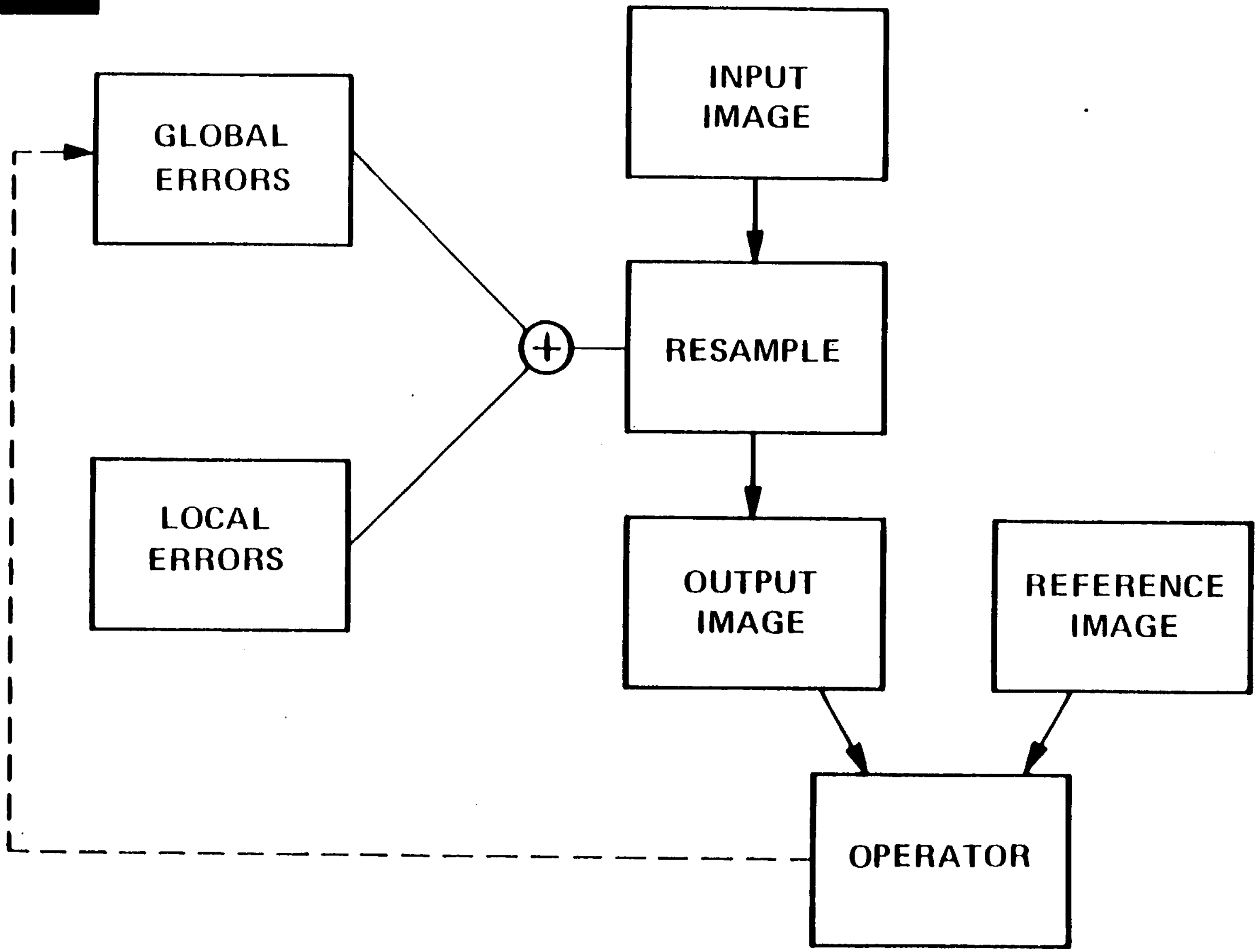
RADARGRAPHICS RESAMPLING SYSTEM



A/N 3185

SPECIFICATION OF PIXEL TRANSFORMATION

- SPACECRAFT DATA
  - POSITION AND ATTITUDE
  - LIMITED ACCURACY
- OPERATOR
  - GROUND CONTROL POINTS
  - VISUAL CHECK

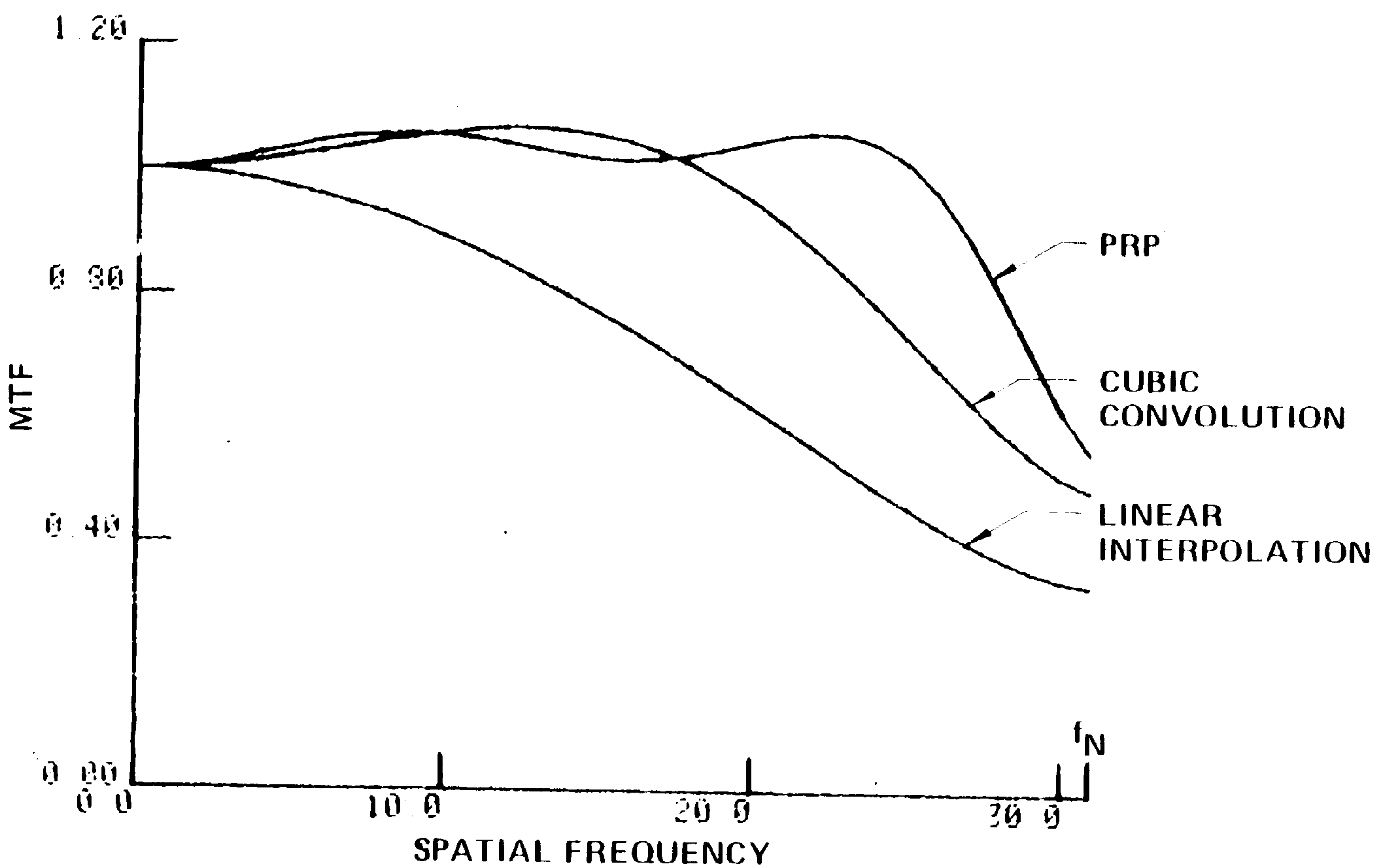
PIPELINE RESAMPLING PROCESSOR

- DEDICATED SIGNAL PROCESSING HARDWARE
- PERFORMS CONVOLUTIONS FOR RESAMPLING
- OPERATES AT 200 MEGABITS / SECOND
- MAINTAINS DATA QUALITY

A/N 3185

9950-947

IMPROVED RESAMPLING MTF



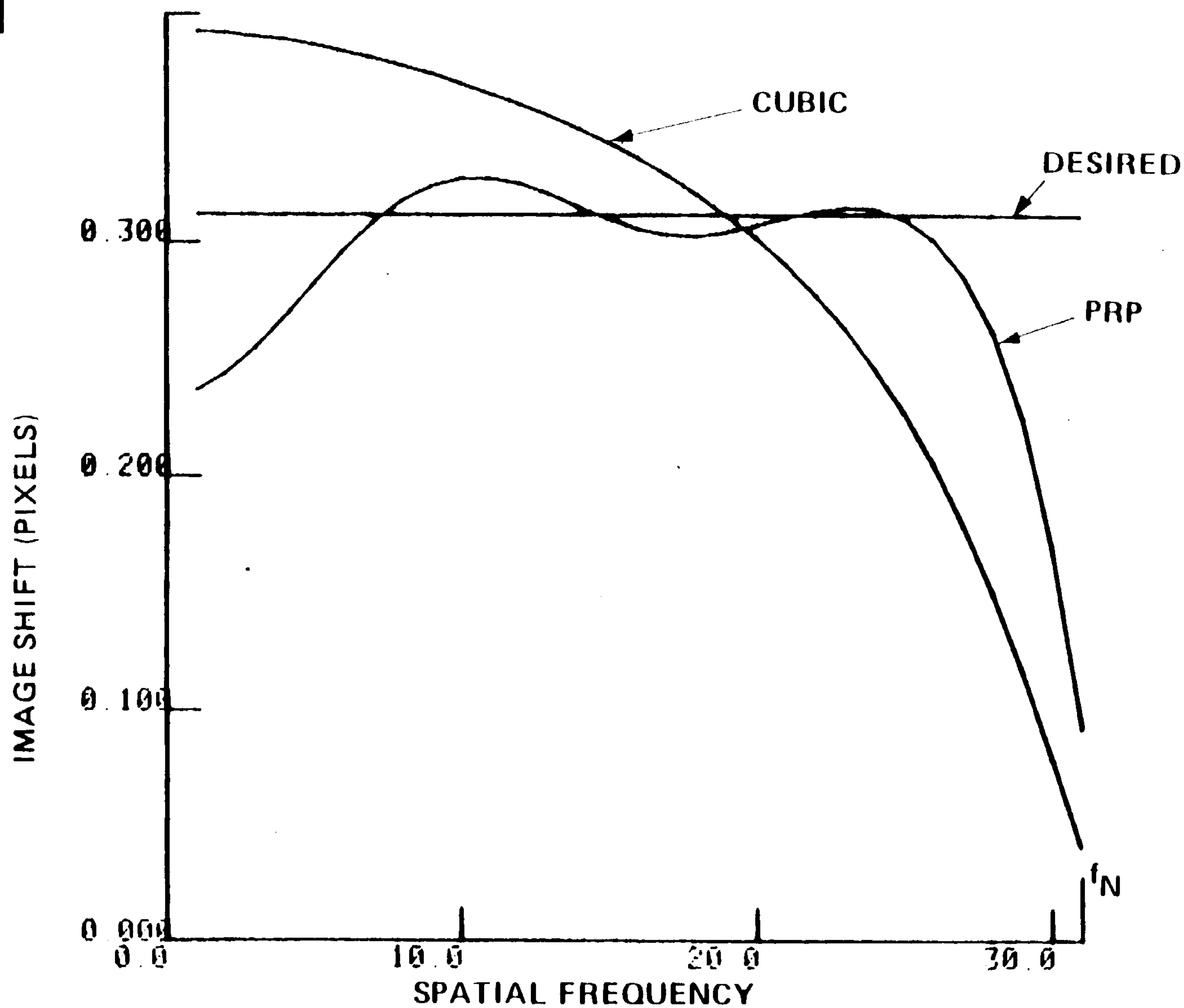
A/N 2460

5/16 PIXEL SHIFT

9950-947

Ball

POSITIONAL ERROR COMPARISON



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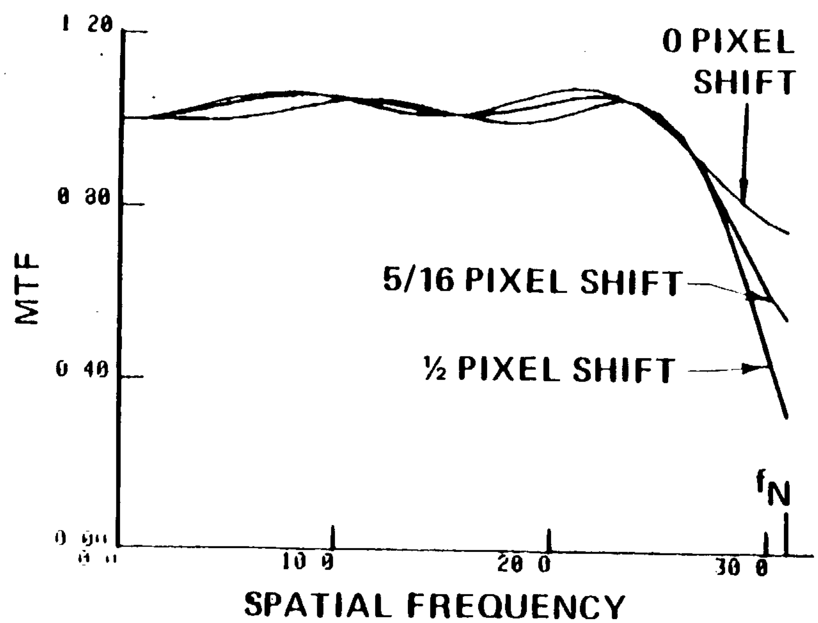
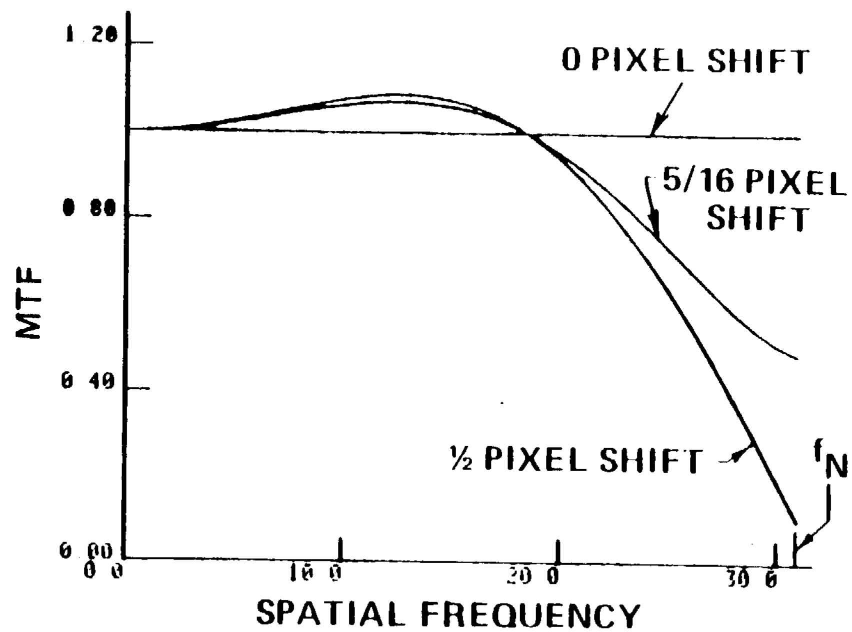
UNIFORMITY OF MTF

PRP



CUBIC CONVOLUTION



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9950-947

BASD IR & D ACTIVITIES INVESTIGATE SPACECRAFT IMAGING SYSTEMS

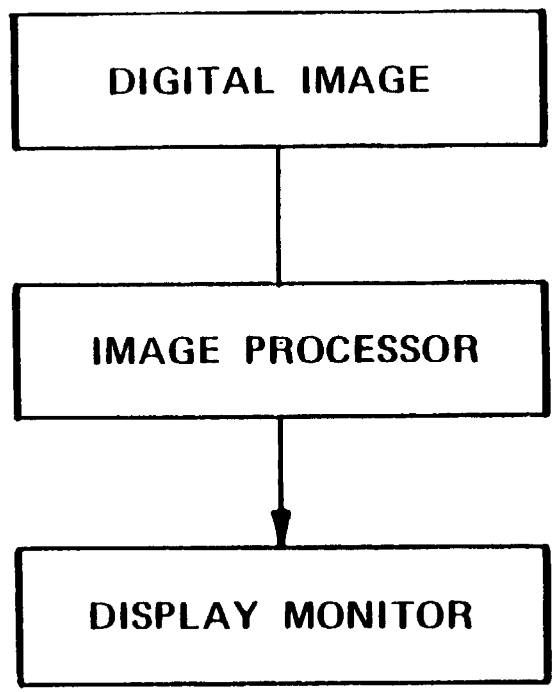
- MODEL SYSTEMS WITH COMPUTER
- OPTIMIZE SYSTEM DESIGN
- IDENTIFY NEED FOR HIGH–SPEED PROCESSORS

A/N 3141

9950-94

Ball

IMAGE PROCESSING SYSTEM FUNCTIONS



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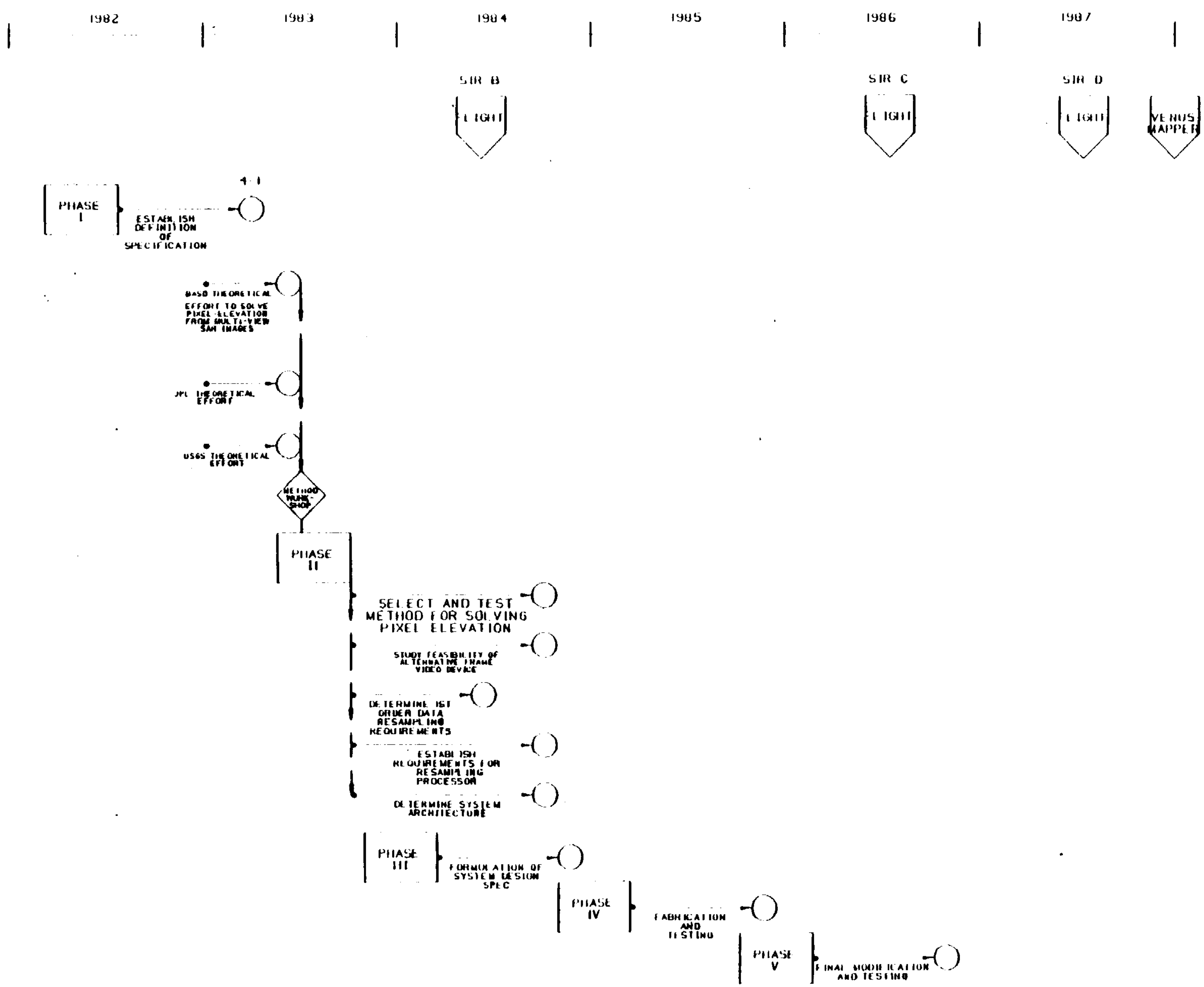
FIVE PHASE RADARGRAPHIC SYSTEM
DEVELOPMENT PLAN



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